Rhythmic activity in the medial and orbital frontal cortices tracks reward value and the vigor of consummatory behavior

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ABSTRACT

This study examined how the medial frontal (MFC) and orbital frontal (OFC) cortices process reward information to guide behavior. We simultaneously recorded local field potentials in the two areas as rats consumed liquid sucrose rewards and examined how the areas collectively process reward information. Both areas exhibited a 4-8 Hz “theta” rhythm that was phase locked to the lick cycle. The rhythm similarly tracked shifts in sucrose concentrations and fluid volumes, suggesting that it is sensitive to general differences in reward magnitude. Differences between the MFC and OFC were noted, specifically that the rhythm varied with response vigor and absolute reward value in the MFC, but not the OFC. Our findings suggest that the MFC and OFC concurrently process reward information but have distinct roles in the control of consummatory behavior.

INTRODUCTION

The medial and orbital frontal cortices (MFC and OFC) are two of the most studied parts of the cerebral cortex for their role in value-guided decision making, a process that ultimately results in animals consuming rewarding foods or fluids. There are extensive anatomical connections between the various parts of the MFC and OFC in rodents (Gabbott et al., 2003; Gabbott et al., 2005; Barreiros et al., 2020), and the regions are part of the medial frontal network (Öngür and Price, 2000). The MFC and OFC are thought to have specific roles in the control of behavior and specific homologies with medial and orbital regions of the primate frontal cortex (MFC: Laubach et al., 2018; OFC: Izquierdo, 2017). The extensive interconnections between MFC and OFC suggest that the two regions work together to control value-guided decisions. Unfortunately, few, if any, studies have examined concurrent neural processing in these regions of the rodent brain as animals perform behavioral tasks that depend on the two cortical regions.

In standard laboratory tasks, the action selection and outcome evaluation phases of value-guided decisions are commonly conceived as separate processes (Rangel et al., 2008). MFC and OFC may contribute independently to these processes or interact concurrently across them. Though there is some variation across published studies, most argue for MFC having a role in action-outcome processing (Alexander and Brown, 2011; Simon et al., 2015) and OFC having a role in stimulus-outcome (stimulus-reward) processing (Gallagher et al., 1999; Schoenbaum and Roesch, 2005; Simon et al., 2015). The present study directly compared neural activity in the MFC and OFC of rats as they performed a simple consummatory task, called the Shifting Values Licking Task, or SVLT (Parent et al., 2015a). Importantly, the task depends on the ability of animals to guide their consummatory behavior based on the value of available rewards, and performance of these kinds of tasks depends on both the MFC (Parent et al., 2015a,b) and OFC (Kesner and Glibert, 2007). The goal of the study was to use the SVLT

to determine if the MFC and OFC have distinct roles in processing reward information, e.g. varying with action (licking) in MFC and the sensory properties of the rewards in OFC.

Most published studies on reward processing used operant designs with distinct actions preceding different outcomes. For example, a rat might respond in one of two choice ports to produce a highly valued reward, delivered from a separate reward port. To collect the reward, the rat has to travel across an operant chamber and then collect a food pellet or initiate licking on a spout to collect the reward. In such tasks (Pratt and Mizumori, 2001; van Durren et al., 2009; van Wiingerden et al., 2010; Riceberg and Shapiro, 2017; Jarovi et al., 2018; Siniscalchi et al., 2019), neural activity during the period of consumption might reflect the properties of the reward, how the animal consumes it, and/or the behaviors that precede reward collection (e.g. locomotion). As such, it is difficult to isolate reward specific activity using such operant designs.

Several published studies have used simpler consummatory and Pavlovian designs, and found neural activity in the MFC is selectively modulated during active consumption (Petykó et al., 2009; Horst and Laubach, 2013; Petykó et al., 2015). None of these tasks used fluids with different reward values. Amarante et al. (2017) was the first study to examine if similar neural activity was associated with animals consuming different magnitudes of reward. The study used the SVLT and presented rats with rewards that differed in terms of the concentration of sucrose contained in the rewarding fluids. The study found that neural actiivty in the MFC is entrained the animals' lick cycle and the strength of entrainment varies with the value of the rewarding fluid, i.e. stronger entrainment with higher value reward. The study also used reversible inactivation methods to demonstrate the licking entrainment depends on neural activity in the MFC.

In the present study, we used the SVLT, and several variations on the basic task design, to study consumption related activity in MFC and OFC. A custom designed syringe pump was used to deliver different volumes of fluid over a common time period (Amarante et al., 2019).

Using the custom device, we were able to directly compare neural activity associated with differences in sucrose concentration and fluid volume. We further manipulated the predictability of changes in reward magnitude to assess how predictable and unpredictable rewards are processed and used a third, intermediate level of reward to assess if reward magnitudes are encoded in a relative or absolute manner. Our findings reveal several similarities – and key differences – in each cortical region across all behavioral tasks that may allude to specific roles for MFC and OFC in the control of consummatory behavior.

METHODS

All procedures carried out in this set of experiments were approved by the Animal Care and Use Committee at American University (Washington, DC). All procedures conformed to the standards of the National Institutes of Health Guide for the Care and Use of Laboratory Animals. All efforts were taken to minimize the number of animals used and to reduce pain and suffering.

Animals

Male Long Evans and Sprague Dawley rats weighing between 300 and 325 g were used in these studies (Charles River, Envigo). Rats were given one week to acclimate with daily handling prior to behavioral training or surgery and were then kept with regulated access to food to maintain 90% of their free-feeding body weight. They were given ~18 g of standard rat chow each day in the evenings following experiments. Rats were single-housed in their home cages in a 12h light/dark cycle colony room, with experiments occurring during the light cycle. A total of 12 rats had a 2x8 microwire array implanted into either the MFC (N=6), the OFC (N=2) or one array in each area contralaterally (N=4). Arrays consisted of 16 blunt-cut 50-μm tungsten (Tucker-Davis Technologies) or stainless steel (Microprobes) wires, separated by 250 μm within each row and 500 μm between rows. *In vitro* impedances for the microwires were ~150 kΩ.

87 *Surgeries*

88 Animals had full access to food and water in the days prior to surgery. Stereotaxic
89 surgery was performed using standard methods. Briefly, animals were lightly anesthetized with
90 isoflurane (2.5% for ~2 minutes), and were then injected intraperitoneally with ketamine (100mg/
91 kg) and dexdomitor (0.25mg/kg) to maintain a surgical plane of anesthesia. The skull was
92 exposed, and craniotomies were made above the implant locations. Microwire arrays were
93 lowered into MFC (coordinates from bregma (AP: +3.2 mm; ML: + 1.0 mm; DV: -1.2 mm from
94 the surface of the brain, at a 12° posterior angle; Paxinos and Watson, 2013) or into OFC (AP:
95 +3.2 mm, ML: + 4.0 mm, DV: -4.0 mm; Paxinos and Watson, 2013). The part of the MFC
96 studied here is also called "medial prefrontal cortex" in many rodent studies and the region is
97 thought to be homologous to the rostral ACC of primates (Laubach et al., 2018). Four skull
98 screws were placed along the edges of the skull and a ground wire was secured in the
99 intracranial space above the posterior cerebral cortex. Electrode arrays were connected to a
100 headstage cable and modified Plexon preamplifier during surgery, and recordings were made to
101 assess neural activity during array placement. Craniotomies were sealed using cyanocrylate
102 (Slo-Zap) and an accelerator (Zip Kicker), and methyl methacrylate dental cement (AM
103 Systems) was applied and affixed to the skull via the skull screws. Animals were given a
104 reversal agent for dexdomitor (Antisedan, s.c. 0.25 mg/ml), and Carprofen (5 mg/kg, s.c.) was
105 administered for postoperative analgesia. Animals recovered from surgery in their home cages
106 for at least one week with full food and water, and were weighed and monitored daily for one
107 week after surgery.

108 *Behavioral Apparatus*

109 Rats were trained in operant chambers housed within a sound-attenuating external
110 chamber (Med Associates; St. Albans, VT). Operant chambers contained a custom-made glass

111 drinking spout that was connected to multiple fluid lines allowing for multiple fluids to be
112 consumed at the same location. The spout was centered on one side of the operant chamber
113 wall at a height of 6.5 cm from the chamber floor. Tygon tubing connected to the back of the
114 drinking spout administered the fluid from a 60 cc syringe hooked up to either a PHM-100 pump
115 (Med Associates) for standard experiments, or to a customized open source syringe pump
116 controller (Amarante et al., 2019) that is programmed by a teensy microcontroller to deliver
117 different volumes of fluid with the same delivery time from one central syringe pump. A "light-
118 pipe" lickometer (Med Associates) detected licks via an LED photobeam, and each lick triggered
119 the pump to deliver roughly 30 μL per 0.5 second. Behavioral protocols were run though Med-
120 PC version IV (Med Associates), and behavioral data was sent via TTL pulses from the Med-PC
121 software to the Plexon recording system.

122 *Shifting Values Licking Task*

123 The operant licking task used here is similar to those previously described (Parent et
124 al., 2015a,b; Amarante et al., 2017). Briefly, rats were placed in the operant chamber for thirty
125 minutes, where they were solely required to lick at the drinking spout to obtain a liquid sucrose
126 reward. Licks to the light-pipe lickometer would trigger the syringe pump to deliver liquid sucrose
127 over 0.5 sec. Every 30 sec, the reward alternated between of high (16% weight per volume) and
128 low (4% wt./vol.) concentrations of liquid sucrose, delivered in a volume of 30 μL. In volume
129 manipulation sessions, the reward alternated between a large (27.85 μL) and small volume
130 (9.28 μL) of 16% liquid sucrose. Rewards were delivered over a period of 0.5 sec for all levels of
131 concentration and volume using a custom made syringe pump (Amarante et al., 2019). The
132 animal's licking behavior was constantly recorded throughout the test sessions.

133 *Blocked versus Randomly Interleaved Licking Task*

134 The Shifting Values Licking Task was altered to allow for comparison of blocked versus
135 interleaved presentations of reward values. The first three minutes of the task consisted of the
136 standard Shifting Values Licking Task, with 30 second blocks of either the high or low
137 concentration sucrose rewards delivered exclusively during the block. After three minutes, the
138 rewards were presented in a pseudo-random order (e.g., high, high, low, high, low, low, high) for
139 the rest of the test session. With rewards interleaved, rats were unaware of which reward would
140 be delivered next. Behavioral and neural data were only analyzed from the first six minutes of
141 each test session. We focused on manipulating sucrose concentration, and not fluid volume, in
142 this task variation, as concentration differences provided the most effects of reward value on
143 licking behavior (see Figure 1D below).

144 *Three Reward Licking Task*

145 The Shifting Values Licking Task was modified, using a third intermediate
146 concentration of sucrose (8% wt./vol) to assess if reward value influenced behavior and
147 neuronal activity in a relative or absolute manner. In the first three minutes of each session, rats
148 received either the intermediate (8%) or low (4%) concentration of sucrose, with the two
149 rewards delivered over alternating 30 second periods as in the SVLT. After three minutes, the
150 rewards switched to the high (16%) and intermediate (8%) concentrations, and alternated
151 between those concentrations for the rest of the session. Behavioral and neural data were only
152 analyzed from the first six minutes of each test session.

153 *Electrophysiological Recordings*

154 Electrophysiological recordings were made using a Plexon Multichannel Acquisition
155 Processor (MAP; Plexon; Dallas, TX). Local field potentials were sampled on all electrodes and

recorded continuously throughout the behavioral testing sessions using the Plexon system via National Instruments A/D card (PCI-DIO-32HS). The sampling rate was 1 kHz. The head-stage filters (Plexon) were at 0.5 Hz and 5.9 kHz. Electrodes with unstable signals or prominent peaks at 60 Hz in plots of power spectral density were excluded from quantitative analysis.

Histology

After all experiments were completed, rats were deeply anesthetized via an intraperitoneal injection of Euthasol (100mg/kg) and then transcardially perfused using 4% paraformaldehyde in phosphate-buffered saline. Brains were cryoprotected with a 20% sucrose and 10% glycerol mixture and then sectioned horizontally on a freezing microtome. The slices were mounted on gelatin-subbed slides and stained for Nissl substance with thionin.

Data Analysis: Software and Statistics

All data were analyzed using GNU Octave (https://www.gnu.org/software/octave/), Python (Anaconda distribution: https://www.continuum.io/), and R (https://www.r-project.org/). Analyses were run as Jupyter notebooks (http://jupyter.org/). Computer code used in this study is available upon request from the corresponding author.

Statistical testing was performed in R. Paired t-tests were used throughout the study and one or two-way ANOVA (with the error term due to subject) were used to compare data for both behavior and electrophysiological measures (maximum power and maximum inter-trial phase coherence) for high and low value licks, blocked versus interleaved licks, and high-intermediate-low licks. For significant ANOVAs, the error term was removed and Tukey's post-hoc tests were performed on significant interaction terms for multiple comparisons. Descriptive statistics are reported as mean $\pm$ SEM, unless noted otherwise.

Data Analysis: Behavior

All rats were first run for at least five standard sessions in the standard Shifting Values Licking Task with differences in concentration (16% and 4% wt./vol.). Rats have been shown to acquire incentive contrast effects in the SVLT after this duration of training (Parent et al., 2015a). For the Blocked-Interleaved and Three Reward tasks, rats were tested after extensive experience in the SVLT and after two “training” sessions with the Blocked-Interleaved and Three Reward designs. The electrophysiological recordings reported here were from the animals’ third session in each task.

Behavioral measures included total licks across the session, the duration and number of licking bouts, and the median inter-lick intervals (inverse of licking frequency). Bouts of licks were defined as having at least 3 licks within 300 ms and with an inter-bout interval of 0.5 sec or longer. Bouts were not analyzed in the Blocked-Interleaved Task; due to the unique structure of the task, bouts were all shortened by default due to a constantly changing reward in the interleaved phase of the task. While bouts of licks were reported in most tasks, electrophysiological correlates around bouts were not analyzed because there were often too few bouts (specifically for the low-lick conditions) in each session to deduce any electrophysiological effects of reward value on bout-related activity.

For analyzing lick rate, inter-lick intervals during the different types of rewards were obtained, and then the inverse of the median inter-lick interval provided the average lick rate in Hertz. Any inter-lick interval greater than 1 sec or less than 0.09 sec was excluded from the analysis. For licks during the randomly interleaved portion of the Blocked-Interleaved Task, more than two licks in a row were needed to calculate lick rate. To analyze behavioral variability of licks, we used coefficient of variation (ratio of the standard deviation to the mean) on high and low value inter-lick intervals that occurred within bouts.

Data Analysis: Local Field Potentials

Electrophysiological data were first analyzed in NeuroExplorer (http://www.neuroexplorer.com/), to check for artifacts and spectral integrity. Subsequent processing was done using signal processing routines in GNU Octave. Analysis of Local Field Potentials (LFP) used functions from the EEGLab toolbox (Delorme and Makeig, 2004) (Event-Related Spectral Power and Inter-Trial Phase Coherence), the signal processing toolbox in GNU Octave (the peak2peak function was used to measure event-related amplitude), and Neurospec 2.11 toolbox (http://www.neurospec.org/) (Directed Coherence). Circular statistics were calculated using the circular library for R. Graphical plots of data were made using the matplotlib and seaborn library for Python. Analyses were typically conducted in Jupyter notebooks, and interactions between Python, R, and Octave were implemented using the rpy2 and oct2py libraries for Python.

To measure the amplitude and phase of LFP in the frequency range of licking, LFPs were bandpass-filtered using eeglab's eegfilt function, with a fir1 filter (Widmann and Schröger, 2012), centered at the rat's licking frequency (licking frequency + inter-quartile range; typically around 4 to 9 Hz), and were subsequently z-scored. Analyses were performed with a pre/post window of 2 seconds, and the Hilbert transform was used to obtain LFP amplitude and phase.

For inter-trial phase coherence (ITC) and event-related spectral power (ERSP), LFP data was preprocessed using eeglab's eegfilt function with a fir1 filter and was bandpass filtered from 0 to 100 Hz. For group summaries, ITC and ERSP matrices were z-scored for that given rat after bandpass filtering the data. Peri-lick matrices were then formed by using a pre/post window of 2 seconds on each side, and the newtimef function from the eeglab toolbox was used to generate the time-frequency matrices for ITC and ERSP up to 30 Hz.

Since most of the lick counts from the Shifting Values Licking Task are generally imbalanced (with a greater number of licks for high versus low value rewards), we used

227 permutation testing to perform analyses on amplitude and phase-locking in these studies. Licks
228 were typically down-sampled to match the lower number of licks. 80% of the number of lower
229 value licks were randomly chosen from each session. For example, if a rat emitted 400 licks for
230 the high concentration sucrose and 200 licks for the low concentration sucrose, then 160 licks
231 would be randomly chosen from each of data type to compare the same number of licks for
232 each lick type. This permutation of taking 80% of the licks was re-sampled 25 times and spectral
233 values were recalculated for each permutation. The maximum ITC value was obtained through
234 calculating the absolute value of ITC values between 2 to 12 Hz within a ~150 ms window (+1
235 inter-lick interval) around each lick. The maximum ERSP value was also taken around the same
236 frequency and time window. Then, the average maximum ITC or ERSP value (of the 25x
237 resampled values) for each LFP channel for each rat was saved in a data frame, and each
238 electrode's maximum ITC and ERSP value for each type of lick (high-value or low-value lick)
239 were used in the ANOVAs for group summaries. Group summary for the peak-to-peak Event-
240 Related Potential (ERP) size recorded the average difference between the maximum and
241 minimum ERP amplitude across all frequencies, using + 1 inter-lick interval window around
242 each lick. The mean ERP size for each electrode for each rat was used in the ANOVAs for
243 group summaries. These analyses were performed for all behavioral variations.

244 RESULTS

245 *Shifting Values Licking Task: Effects of reward magnitude on consummatory behavior*

246 The Shifting Values Licking Task (Amarante et al., 2017; Figure 1A) was used to
247 assess reward encoding across the MFC and OFC as 12 rats experienced shifts in reward value
248 defined by differences in sucrose concentration or fluid volume. Shifts in concentration were
249 between 16% and 4% sucrose in a volume of 30 μL. Shifts in volume were between 30 μL and
250 10 μL containing 16% sucrose. Concentrations and volumes alternated over periods of 30 sec

(Figure 1B, left). LFP activity was recorded from 16-channel multi-electrode arrays in the MFC in 10 of the 12 rats and OFC in 6 of the 12 rats (Supplementary Figure 1).

Several measures of licking behavior varied with sucrose concentration or fluid volume: lick counts, inter-lick intervals, lick rate, and bout duration (Figure 1C). All rats licked more for the high concentration reward compared to the low concentration reward (paired t-test; $t(11)=10.76$, $p<0.001$) (Figure 1D). Rats also licked at a faster rate for the high concentration reward compared to the low concentration reward (paired t-test; $t(11)=6.347$, $p<0.001$) (Figure 1E). Additionally, rats had increased bout durations when licking for the high concentration reward compared to the low concentration reward (paired t-test: $t(11)=2.9439$, $p=0.013$) (Figure

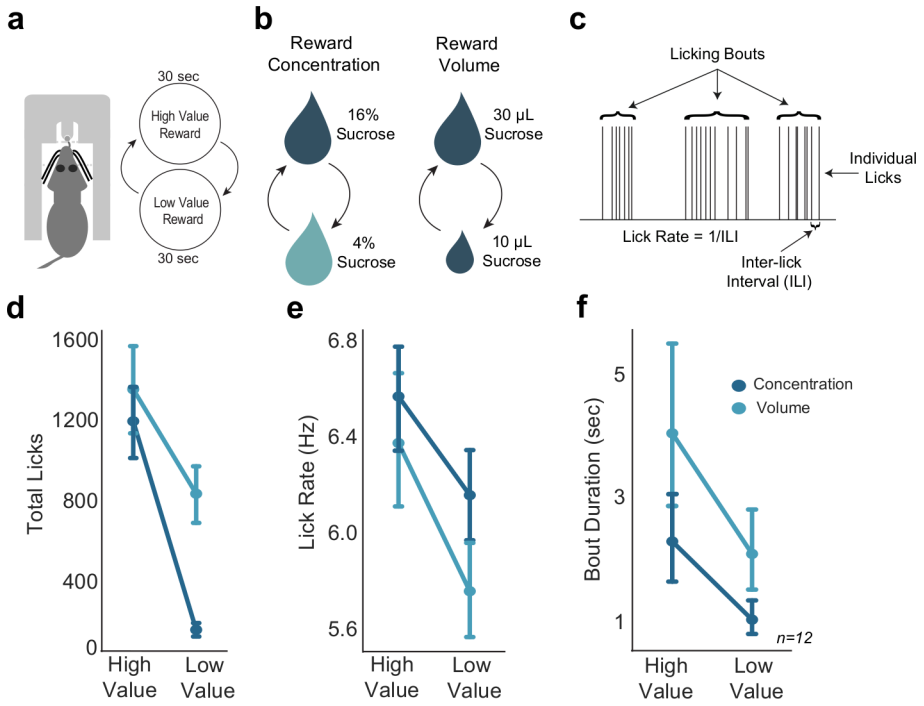

Figure 1. Consummatory behavior tracked shifts in sucrose concentration and fluid volume. A. In the Shifting Values Licking Task, rats received access to one of two values of reward, with rewards alternating every 30 sec. B. Manipulation of reward value by changing either concentration or volume. C. Types of behavioral licking measurements recorded in all licking tasks. D,E,F. Rats licked more (D), faster (E), and over longer bouts (F) for the high concentration and large volume rewards. Error bars represent SEM.

1F). There was no difference in variability of high or low concentration licks: the coefficient of variation for inter-lick intervals was the same (paired t-test: t(9)=0.864, p=0.41).

Rats behaved similarly when consuming the high concentration and large volume rewards. In volume manipulation sessions, rats emitted more licks for the large reward than the small reward (paired t-test; t(11)=4.99, p<0.001). However, this difference in lick counts was less robust than the difference in high and low concentration rewards during concentration manipulation sessions (Figure 1D). Rats licked at a faster rate for large rewards compared to

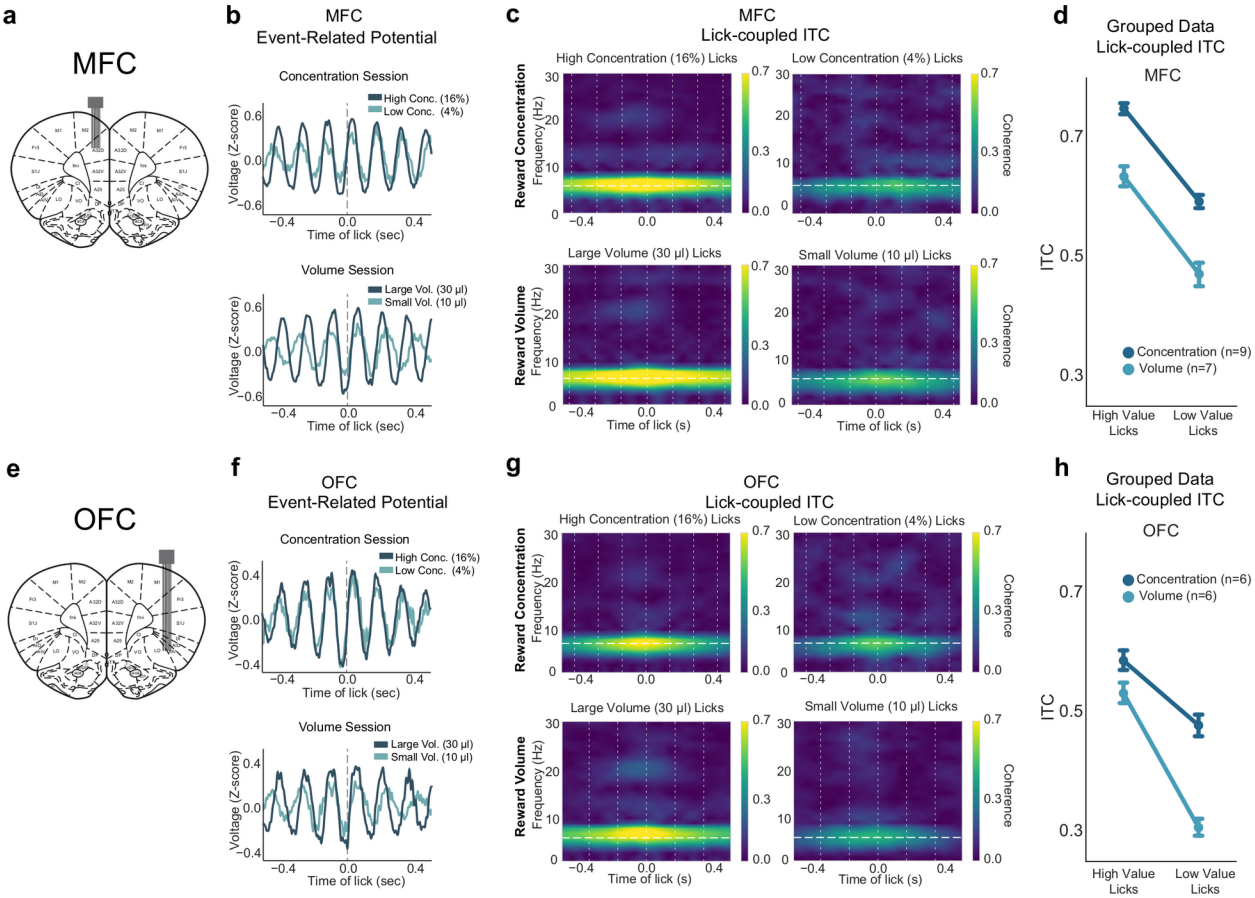

Figure 2. Lick-entrained neural activity in MFC and OFC tracked shifts in sucrose concentration and fluid volume. A,E. Rats were implanted with a 2x8 electrode array in either MFC (A) or OFC (E). B,F. Event-related potentials during concentration and volume manipulation sessions in the Shifting Values Licking Task for MFC (B) and OFC (F). C,G. Spectral ITC time-frequency plots revealed strong phase locking during licks for the high concentration and large volume (left sides) rewards in both MFC (C) and OFC (G). Plots are from one electrode from one individual animal. ITC is consistently strongest around 4-8 Hz. D,H. Grouped data from all rats in both concentration and volume sessions in MFC (D) and OFC (H) showed strongest ITC during licks for the high value reward. Error bars represent SEM.

small volume rewards (paired t-test; $t(11)=6.311$, $p<0.001$) (Figure 1E), and licking bouts were longer for large rewards compared to bouts to consume small rewards (Figure 1F), (paired t-test; $t(11)=2.569$, $p=0.027$).

Shifting Values Licking Task: Lick entrainment in MFC and OFC tracks reward magnitude

We next aimed to determine if there were electrophysiological differences in MFC and OFC during access to the different types of rewards. We focused on three key measurements of local field potential (LFP) activity: amplitude (as measured by the amplitude of the ERP; Supplementary Figure 2A), spectral power (as measured by ERSP; Supplementary Figure 2B), and phase (as measured by ITC, Supplementary Figure 2C). We recorded LFP activity from both cortical areas as rats consumed the different types of rewards (concentration or volume) in the Shifting Values Licking Task (Figure 2A,E).

Similar to Amarante et al. (2017), LFP activity in MFC was entrained to the lick cycle and varied with value (Figure 2B-D, top). Uniquely, we found similar lick-entrained activity in OFC that also varied with value (Figure 2F-H). Time-frequency analyses for both cortical areas revealed elevated ITC between 4 and 8 Hz for licks that delivered the high concentration liquid sucrose but not the low concentration sucrose (Figure 2C,G). That is, the phase angles of the LFP fluctuations were more consistent when rats consumed the high concentration fluid compared to the low concentration fluid. This result was observed in all rats that were tested (dark blue lines in Figure 2D,H) (MFC: $F(1,278)=443$, $p<0.001$; OFC: $F(1,177)=77.31$, $p<0.001$; one-way ANOVAs with an error term for within-subject variation). Analysis of phase coherence (Supplementary Figure 2D) and event-related power (Supplementary Figure 2E) revealed effects solely in the 4-8 Hz (theta) frequency range.

To assess differences in power, we used a peak-to-peak analysis of ERPs during licks for the high-value and low-value rewards. The measure calculates the difference in the maximum and minimum ERP amplitude using a window centered around each lick. The size of the window was twice each rat's median inter-lick interval. LFPs in MFC showed increased amplitudes for high concentration rewards, as opposed to low concentration rewards (one-way ANOVA: $F(1,278)=34.19$, $p<0.001$). Figure 2B shows MFC ERPs for high and low concentration rewards of an example rat. This effect was not significant in OFC ERPs, as seen in Figure 2F ($F(1,177)=0.557$, $p=0.456$). We also measured ERSP, and found a decrease in MFC power from licks for the high to low concentration rewards specifically in the 4-8 Hz range ($F(1,278)=18.72$, $p<0.001$; one-way ANOVA); there was no major difference in ERSP measures in OFC ($F(1,177)=0.039$, $p=0.843$).

We then manipulated the size of the reward and recorded LFP activity from MFC and OFC. Unlike the variable concentration session, event-related potentials in MFC or OFC alone did not distinguish between large versus small volume rewards (MFC: $F(1,216)=0.865$, $p=0.354$; OFC: ($F(1,179)=1.876$, $p=0.173$); one-way ANOVAs) (Figure 2B,F, bottom). There was no major difference in event-related spectral power during licks for large or small rewards in MFC or OFC (MFC: $F(1,216)=0.877$, $p=0.35$; OFC: $F(1,179)=1.76$, $p=0.186$); one-way ANOVAs). However, in both MFC and OFC, rats showed similar 4-8 Hz phase-locking for large rewards (Figure 2C,G, bottom), closely resembling what we observed with high concentration rewards (Figure 2C,G, top), which was significantly increased from phase-locking for small rewards (MFC: $F(1,216)=138.5$, $p<0.001$; OFC: $F(1,179)=280.8$, $p<0.001$; one-way ANOVA). This effect was consistent across all rats tested (light blue lines in Figure 2D,H).

These findings suggest that LFP activity in both MFC and OFC similarly encodes aspects of preferred, versus less preferred, reward options. 4-8 Hz phase-locking was strongest for both the high concentration and large volume rewards, which may be evidence that the

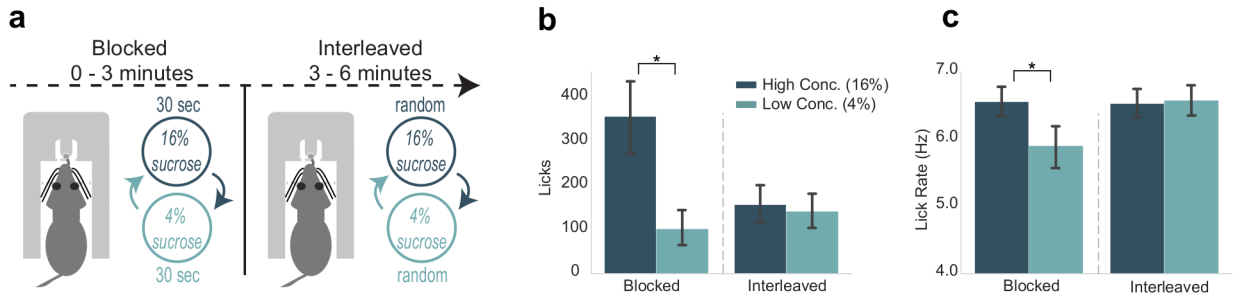

Figure 3. Engagement in and the vigor of licking varied with reward expectation. A. Rats participated in a modification of the Shifting Values Licking Task, called the Blocked-Interleaved Task, in which they received alternating access to high and low concentrations of liquid sucrose for three minutes and then received interleaved (and thus unpredictable) presentations of the two levels of sucrose for the rest of the session. B. Total licks emitted for both high and low concentration rewards during the blocked and interleaved portion of the task. Rats licked less for both rewards when rewards were randomly interleaved. C. Lick rate was similar for both rewards in the interleaved, but not blocked, portion of the task. Asterisk denotes $p<0.05$. Error bars represent SEM.

animal is acting within a preferred state with the goal of obtaining their most "valued" reward. These findings provided further evidence suggesting that the entrainment of neural activity in MFC and OFC to the lick cycle tracks reward magnitude.

Blocked-Interleaved Task: Engagement in and the vigor of licking vary with reward expectation

The same group of 12 rats were subsequently tested in an adjusted version of the Shifting Values Licking Task, which will be referred to as the Blocked-Interleaved Task (Figure 3A). In the first three minutes of the task, i.e. the "blocked" phase, rats behaviorally showed their typical differentiation of high versus low concentration rewards by emitting more licks for the high concentration reward (Figure 3B, left), and licked at a faster rate (Figure 3C, left). However, this pattern changed when the rewards were randomly presented in the "interleaved" part of the task. With a randomly interleaved reward presentation, rats licked nearly equally for high and low concentration rewards (Figure 3B, right). We performed a two-way ANOVA on the number of licks by each lick type (high or low concentration) and portion of the task (blocked or interleaved). There was a significant interaction between concentration of reward and the

blocked or interleaved portion of the task (F(1,33)=24.51, p<0.001). Post-hoc analyses revealed that while there was a significant difference in high and low concentration licks during the blocked portion (p<0.001), there was no difference between high and low concentration licks during the interleaved portion of the task (p=0.98).

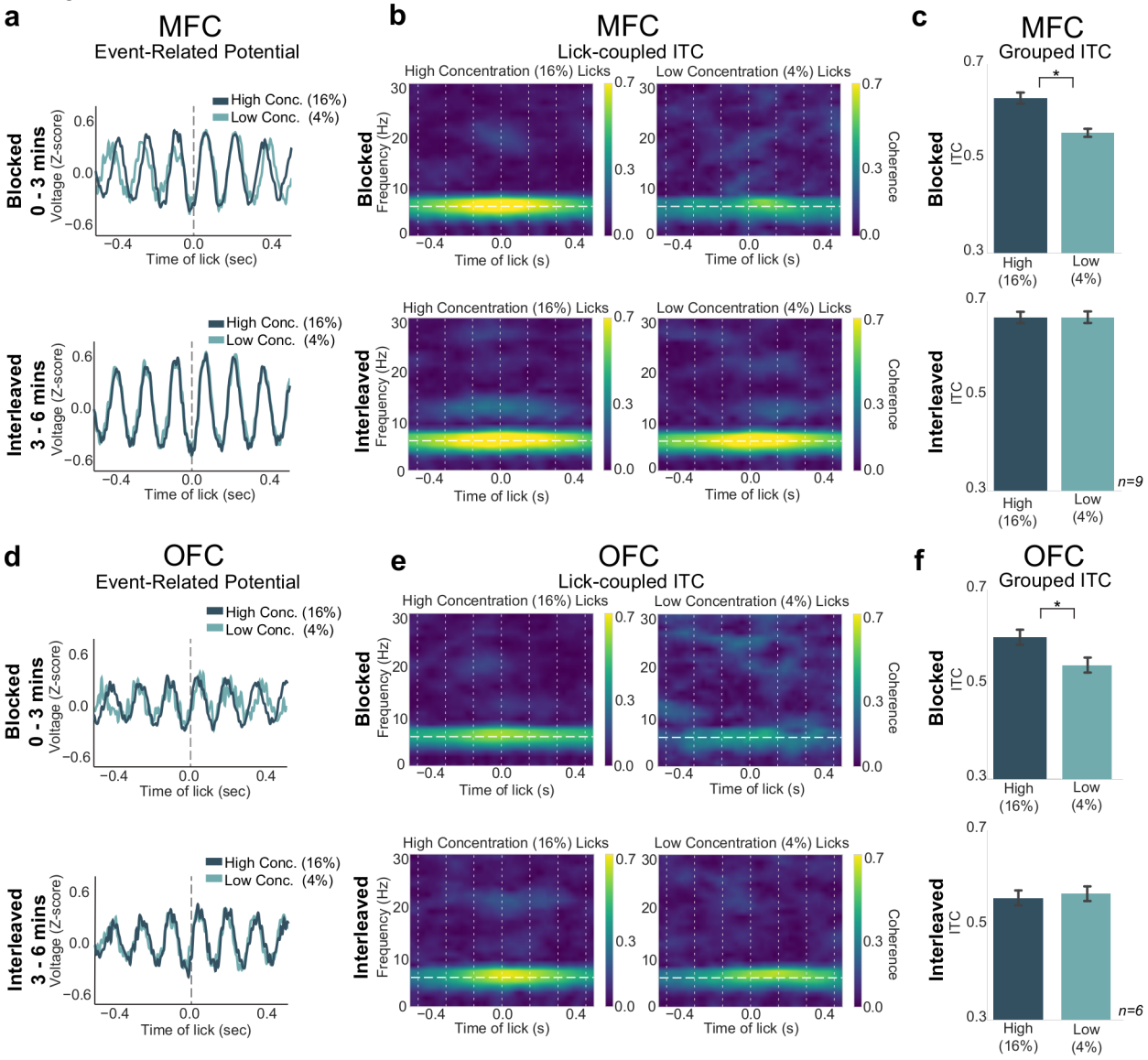

Figure 4. Lick-entrained neural activity varied with reward expectation. A,D. ERPs for licks of both rewards in MFC (A) and OFC (D) remain unchanged during the interleaved portion of the task. B,E. Spectral ITC plots revealed stronger 4-8 Hz phase-locking during licks for the high concentration reward in the blocked portion (top), but phase-locking during licks for high and low concentration rewards in the interleaved portion were indistinguishable from each other. C,F. Grouped data revealed no difference in ITC values during high or low concentration licks in the interleaved phase. Asterisk denotes p<0.05. Error bars represent SEM.

332 Additionally, there was a significant difference in lick rate by each lick type and portion
333 of the task ($F(1,33)=23.13$, $p<0.001$; two-way ANOVA) (Figure 3C). Post hoc analyses revealed
334 that rats licked significantly faster for high versus low concentration rewards during the blocked
335 portion ($p<0.005$). Lick rates for high versus low concentration licks during the interleaved part
336 of the task were not significantly different ($p=0.99$). Notably, lick rate during access to either
337 high concentration ($p=0.005$) or low concentration ($p=0.002$) rewards during the interleaved
338 portion was significantly increased from lick rate during access to the low concentration reward
339 in the blocked portion of the task.

340 *Blocked-Interleaved Task: Dissociation of MFC and OFC with regards to response vigor*

341 Having established that the Blocked-Interleaved Task can reveal effects of reward
342 expectation on task engagement and response vigor, we next examined how neural activity in
343 the MFC and OFC varies with these behavioral measures. We assessed changes in lick-
344 entrained ERPs and their amplitudes (Figure 4A,D), ERSP, and ITC (phase-locking) (Figure 4B-
345 C,E-F). LFPs in MFC and OFC showed strong 4-8 Hz phase-locking during licks for the high
346 concentration rewards in the blocked phase of the task (Figure 4B,E). We performed a two-way
347 ANOVA on maximum ITC values (Figure 4C,F) from LFPs in both MFC and OFC for each rat
348 and each electrode channel with interaction terms for lick type (high or low concentration
349 reward) and portion of the task (blocked or interleaved reward access), and found a significant
350 interaction of lick type by portion of the task (MFC: $F(1,572)=10.45$, $p=0.001$); OFC:
351 $F(1,363)=12.119$, $p<0.001$). Post-hoc analyses revealed that while there was a significant
352 difference in phase-locking of licks for high versus low concentration in the blocked portion
353 (MFC: $p<0.001$; OFC: $p<0.036$), there was no difference in phase-locking of licks for high versus
354 low concentration rewards in the interleaved portion of the task (MFC: $p=0.999$; OFC: $p=0.973$).

In MFC, a two-way ANOVA revealed a significant interaction of lick type by portion of the task with ERP peak-to-peak size (Figure 4A) as the dependent variable ($F(1,564)=6.232$, $p=0.013$). However, there were no differences between the ERP measures between high and low concentration licks during the blocked portion of the task ($p=0.887$) and between high and low concentration licks during the interleaved portion of the task ($p=0.938$). The same was true with ERSP measures for MFC LFPs; There was a significant interaction between lick type and portion of the task ($F(1,564)=30.17$, $p<0.001$; two-way ANOVA), but no significant difference between ERSP values between high and low concentration licks in the blocked ($p=0.213$) or interleaved ($p=0.743$) portions of the task. In OFC (Figure 4D), there was no significant interaction of lick type and portion of the task by the amplitude size of the lick's ERPs ($F(1,363)=0.131$, $p=0.718$; two-way ANOVA), and no difference in OFC ERSP values of lick type by portion of the task either ($F(1,363)=0.744$, $p=0.389$; two-way ANOVA).

We wanted to further investigate potential differences in MFC and OFC in the Blocked-Interleaved Task, since initial results show a general increase of ITC values from MFC in the interleaved portion of the task and a general decrease in ITC values from OFC. This was

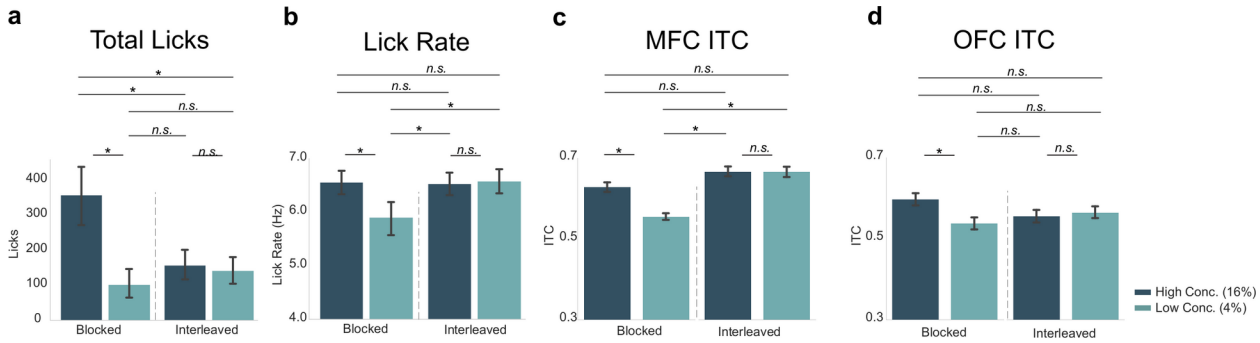

Figure 5. Neural activity in MFC, but not OFC, varied with the lick rate (vigor) and not task engagement (total licks). Post-hoc contrasts of statistically significant effects revealed by two-way ANOVA. Direct comparison of behavioral measures (A – total licks; B – lick rate) with MFC ITCs (C) and OFC ITCs (D) showed a similar pattern (and identical post-hoc statistical contrasts) between lick rate (B) and MFC ITCs (C). The pattern of post-hoc contrasts for OFC ITCs (D) did not match either total licks or lick rate. Asterisk denotes $p<0.05$. Error bars represent SEM.

370 of particular interest since MFC ITC values varied with the lick rate, which increased for both the
371 high and low concentration licks in the interleaved portion of the task.

372 We directly compared ITC values in both regions with lick rate and total lick counts
373 (Figure 5). Post-hoc analyses displayed in Figure 5C revealed that in MFC there was a
374 significant difference between ITC values for the high versus low concentration licks (as also
375 documented at the top of Figure 4C), but ITC values for high concentration licks during the
376 blocked portion of the task did not differ from ITC values for either the high ($p=0.075$) or low
377 concentration ($p=0.089$) conditions in the interleaved portion of the task. The pattern of post-hoc
378 contrasts matches the lick-rate data (Figure 5B) for all paired comparisons. This match includes
379 the finding (Figure 5C) that ITC values for low concentration licks in MFC differed from all three
380 of the other conditions (high concentration blocked, high concentration interleaved, and low
381 concentration interleaved licks; $p<0.001$ for each comparison). The MFC ITC post-hoc test
382 results (Figure 5C) did not match the pattern for total licks (Figure 5A).

383 In OFC, ITC values (Figure 5D) did not match either the total-lick (Figure 5A) or lick-
384 rate (Figure 5B) comparisons, despite the qualitative similarity with the total number of licks
385 (compare Figure 5D with Figure 5A). The only significant difference in ITC values in OFC was
386 between the high and low concentration licks in the blocked portion of the task (as also
387 documented at the top of Figure 4F). All other comparisons were non-significant. This pattern of
388 post-hoc comparisons did not match either total licks (compare Figure 5A with 5D) or lick rate
389 (compare Figure 5B with 5D).

390 Together with the results summarized in Figure 4, these findings from post-hoc testing
391 in Figure 5 provide evidence that MFC and OFC encode different aspects of licking and reward
392 value. There was a clear match between the pattern of lick entrainment in the MFC, but not the
393 OFC, with the animals' licking rates. The correspondence between lick entrainment in MFC and
394 the animals' lick rates provides support for the idea that MFC plays a role in response vigor. By

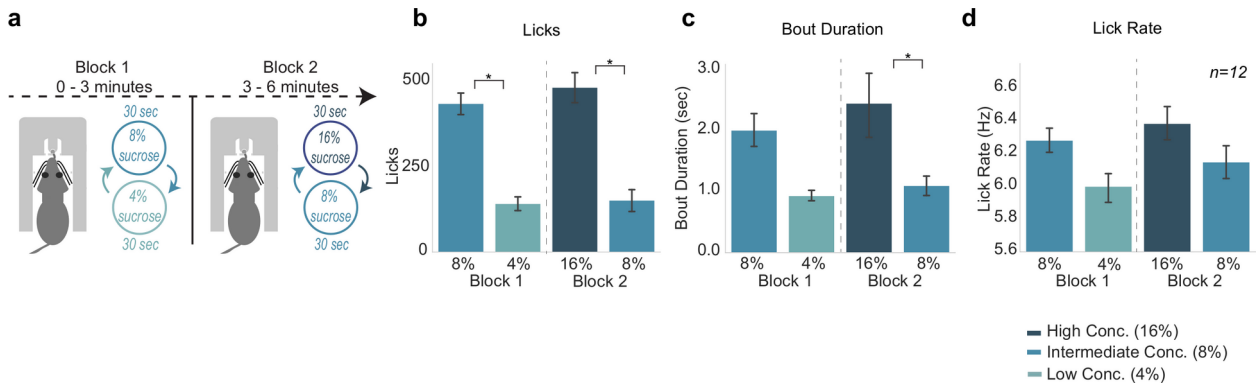

Figure 6. Consummatory behavior tracked relative differences in reward value. A. The Three Reward Task is a variation of Shifting Values Licking Task but with a third reward introduced. In the first block of the task, rats experience the intermediate (8%) reward and low (4%) reward. In block 2, rats experience the high (16%) reward paired with the intermediate (8%) reward. B. Rats licked more for the sweeter reward in each block. C. Rats showed greater bout durations for the sweeter reward. D. Lick rate showed a similar pattern to licks and bout duration, but was not statistically significant. Asterisk denotes $p<0.05$. Error bars represent SEM.

contrast, OFC might be involved in more general aspects of motivation, e.g. to lick or not (reward evaluation) based on reward magnitude or the predictability of the environment.

Three Reward Task: Behavioral evidence for effects of relative reward value

The previous experiments assessed comparison of two levels of rewards (either high/low concentration or large/small volume) in the Shifting Values Licking Task. After seeing clear behavioral and electrophysiological differences between two rewards, we aimed to investigate how animals process reward with contexts involving three different rewards. In this experiment, we assessed if rats process rewards in a relative manner or in an absolute manner by implementing a third intermediate (8% wt./vol. sucrose concentration) reward.

In the Three Reward Task (Figure 6A), the first block consists of the Shifting Values Licking Task with 30 sec shifts between the intermediate value (8% sucrose) reward and the low value (4% sucrose) reward. After 3 minutes the second block of the task begins, where rats then experience shifting values of reward from the high value (16% sucrose) reward to the

408 intermediate value (8% sucrose) reward. This allowed us to assess how rats would process the
409 intermediate 8% sucrose reward when it is paired with a worse (4%) or better (16%) option
410 within one session. Additionally, the design introduces a second context (just like in the
411 Blocked-Interleaved Task previously) in which we could assess if animals are still processing a
412 (temporally) local comparison of reward types.

413 Licking varied with both reward value and block, i.e. low vs intermediate and
414 intermediate vs high ($F(3,33)=34.2$, $p<0.001$) (Figure 6B). Post-hoc analyses revealed that rats
415 emitted significantly more licks for the intermediate value 8% reward as opposed to the low
416 value 4% reward in block 1 ($p<0.001$). In block 2, rats also emitted significantly fewer licks for
417 the intermediate value 8% reward when it was paired with the high value 16% reward ($p<0.001$).
418 Rats also licked significantly less for the intermediate 8% reward in block 2 than they did in
419 block 1 ($p<0.001$).

420 There was a more subtle effect for differences in bout duration across the different
421 rewards ($F(3,33)=5.333$, $p=0.004$; two-way ANOVA) (Figure 6C). Post-hoc analyses revealed
422 no significant difference in bout duration for the 4% versus 8% in block one ($p=0.098$), yet there
423 was a significant decrease in bout durations during access to the 8% versus 16% in block two
424 ($p=0.023$). Bout durations during access to the intermediate 8% reward in block 1 versus block
425 2 were not different ($p=0.20$). While there was a significant effect of lick type on lick rate
426 ($F(3,33)=10.59$, $p<0.001$; two-way ANOVA), post-hoc analyses revealed no major differences in
427 lick rate of the licks for rewards in block 1 ($p=0.17$) or block 2 ($p=0.31$) (Figure 6D),nor for the
428 lick rate for 8% licks in block 1 versus block 2 ($p=0.76$).

429 *Three Reward Task: Neural evidence for effects of absolute, not relative, reward value*

430 The behavioral measures summarized above established that the Three Reward Task
431 can reveal effects of relative value comparisons. We next analyzed electrophysiological signals

from MFC and OFC (Figure 7) to determine if they tracked the animals' behavior in the task, and might encode relative differences in value, or some other aspect of value, such as the absolute differences between the three rewards. We found a significant difference between ITC values for the three different rewards in both MFC and OFC (MFC: $F(3,627)=154.4$, $p<0.001$; OFC: $F(3,363)=13.29$, $p<0.001$; two-way ANOVAs). Tukey post-hoc analyses revealed a difference in

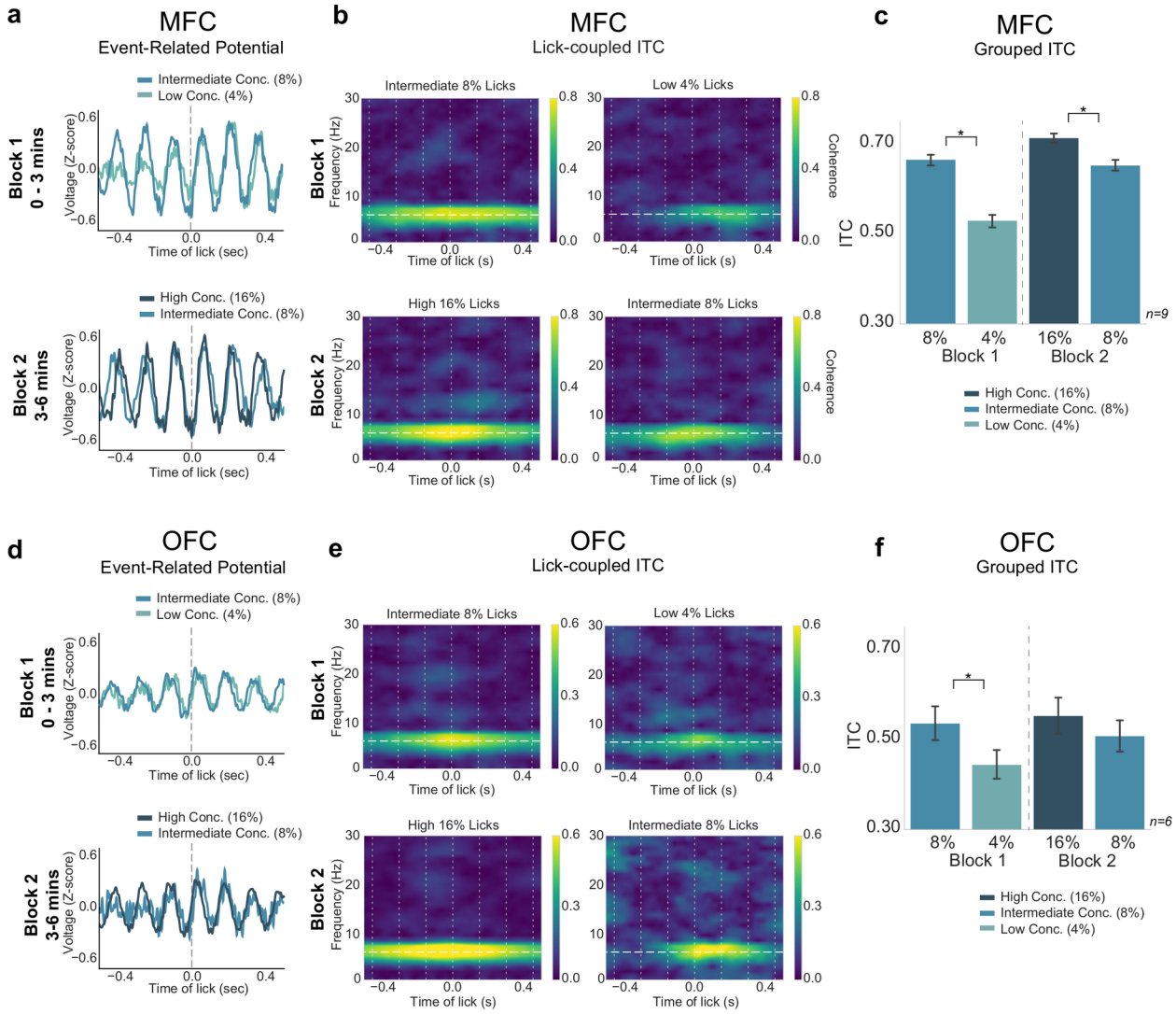

Figure 7. Neural activity in MFC, but not OFC, tracked absolute differences in reward value. A,D. ERPs for each block of the task from MFC (A) and OFC (D). B,E. ITC values in MFC (B) and OFC (E) showed strongest 4-8 Hz phase locking for the "high value" reward in each block. C,F. Group data revealed significantly greater ITC values for the high value reward in each block for MFC ITCs (C), and a similar pattern was found in OFC (F) but only block 1 rewards were significantly different. Asterisk denotes $p<0.05$. Error bars represent SEM.

ITC values between intermediate and low licks in block 1 (MFC: p<0.001; OFC: p=0.003), and a difference in ITCs between high and intermediate licks in block 2 for MFC only (MFC: p<0.005; OFC: p=0.313) (Figure 7B-C,E-F). There was no difference between ITC values from intermediate (8%) block 1 and intermediate block 2 licks in both regions (MFC: p=0.881; OFC: p=0.705).There was a significant difference between MFC ITC values for block 1 intermediate (8%) licks and block 2 high (16%) licks (p=0.028), as well as a significant difference between MFC ITC values for block 1 low (4%) licks and block 2 intermediate (8%) licks (p<0.001). Signals from the OFC did not differ across these conditions.

Peak to peak amplitude analysis of the Three Reward Task revealed a significant effect of block on MFC LFP amplitude across lick types (F(3,627)=15.56, p<0.001; two-way ANOVA) (Figure 7A). Tukey post-hoc testing revealed no relevant significant differences between ERP size in MFC (between block 1 intermediate and low licks: p=0.864; between block 2 high and intermediate licks: p=0.944). There was no difference in OFC amplitude size (F(3,363)=0.827, p=0.479, two-way ANOVA) (Figure 7D). While there was a significant effect for ERSP values in both MFC and OFC (MFC: F(3,627)=18.35, p<0.001; OFC: F(3,363)=5.108,

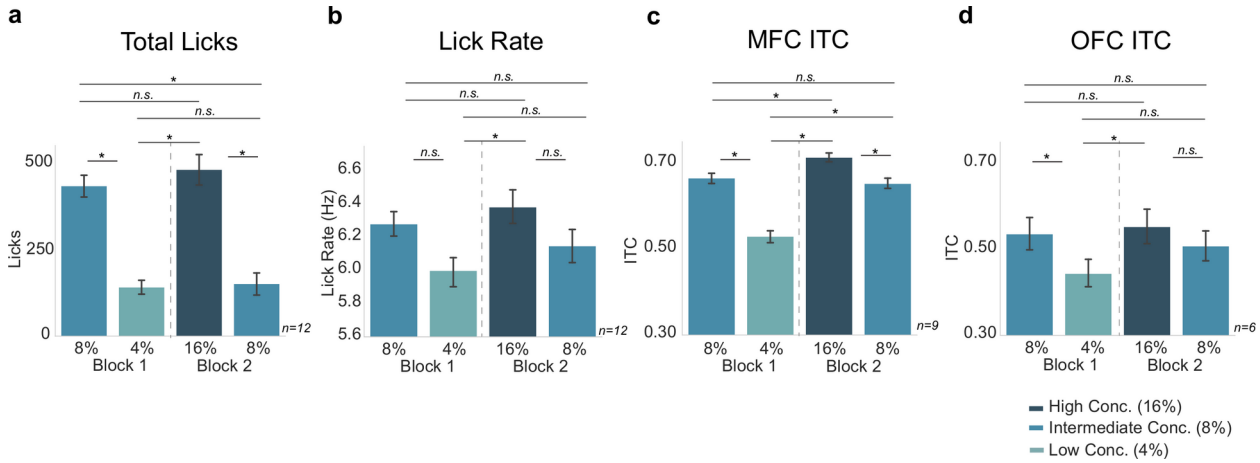

Figure 8. Neural activity in MFC, but not OFC, varied with effects of absolute reward value on lick rate (vigor) and task engagement (total licks). A,B. Behavioral measures replotted with significance bars for each combination reward. MFC ITCs (C) did not show the exact same pattern as lick rate, which is different from Figure 5. OFC ITCs (D) did not look like total licks or lick rate. Asterisk denotes p<0.05. Error bars represent SEM.

452 p=0.002; two-way ANOVAs), none of the relevant measures were significant (block 1
453 intermediate and low licks: MFC: p=0.875; OFC: p=0.492; block 2 high and intermediate licks:
454 MFC: p=0.637; OFC: p=0.999).

455 The ITC findings, at least in MFC, support the idea that the “higher value” and “lower
456 value” rewards in each context are being encoded differently across contexts. They indicate that
457 MFC encodes absolute reward value. Qualitatively, the ITC values in MFC seem to have the
458 same pattern as the lick rate (Figure 8B,C), similar to how MFC values reflected lick rate in the
459 Blocked-Interleaved Task. However, post-hoc statistical testing revealed important differences.
460 For example, the ITC in MFC differed significantly for high- vs. low-value rewards in both blocks
461 1 and 2, but lick rate did not. Importantly, post-hoc analyses revealed a significant difference in
462 ITC values in MFC for every reward combination except for the intermediate block 1 and
463 intermediate block 2 rewards, which is evidence for absolute encoding of value (see
464 Supplementary Figure 3A-B).

465 The encoding of value was less clear based on ITC measures from the OFC. These
466 values did not directly match the licking behavior (in either rate, total licks, or bout duration)
467 (compare Figure 8A,B with 8D), and did not show clear evidence for either absolute or relative
468 encoding of reward. Instead, the results from Figure 8D indicate that OFC encodes reward
469 value in a mixed absolute/relative manner (as in Supplementary Figure 3C).

470 DISCUSSION

471 We investigated the role of MFC and OFC in processing reward information as rats
472 participated in various consummatory licking tasks. Rats process and express changes in
473 reward size in roughly the same manner as with reward concentration, both behaviorally and
474 electrophysiologically. LFP activity in both MFC and OFC is sensitive to changes in reward type
475 (both volume and concentration). Our results reveal context-dependent value signals in both
476 regions through randomly presented rewards and by introducing a third reward in the task.

Behaviorally, rats show evidence for a relative expression of rewards, while neural activity in MFC, but not OFC, shows an absolute encoding of reward value. Together, our findings suggest that rats sample rewards and commit to consuming a given reward when they are able to predict its value, and this behavior is coupled to neural activity in MFC and OFC that encode both the value of the reward and the animal's consummatory strategy. The subtle differences between the two regions follow the hypothesis that MFC represents action-outcome relationships and OFC represents stimulus-outcome relationships. MFC activity may provide the "value of the action" information to OFC, while OFC may evaluate the reward and provides feedback to MFC.

Rhythmic Activity and Reward Processing

Similar to our previous studies (Horst and Laubach, 2013; Amarante et al., 2017), neural activity was entrained to the lick cycle across all tasks in both MFC and OFC. Entrainment was strongest for the high-value reward (either of size or sweetness) and varied with the animals consummatory strategy (persistently lick a highly preferred option or sample fluid and wait for better option). Previous studies have viewed this rhythmic activity as being driven by the act of licking, as rats naturally lick at 6-7 Hz (Travers et al, 1997; Weijnen, 1998; Host and Laubach, 2013). However, the activity cannot be explained solely by licking, as there are instances where phase-locking and behavior do not show the same pattern (e.g. the Blocked-Interleaved experiment), and the variety of studies reported here and in Amarante et al. (2017) suggest a higher order role for the neural activity in the control of consummatory behavior.

Specifically how the rhythmic activity contributes to the control of behavior might be best understood by considering how this general frequency range has been interpreted in other types of behavioral tasks. Rhythms between 4 and 8 Hz are commonly referred to as "theta

activity" and those found in the frontal cortex have been referred to as "frontal theta" (Cavanagh and Frank, 2014). There have been several proposals for the role of frontal theta in information processing. One idea is that the rhythm acts to break up sensory information into temporal chunks (Uchida and Mainen, 2003), and is related to the notion of a global oscillatory signal to synchronize neural activity across multiple brain structures throughout the taste-reward circuit (Gutierrez and Simon, 2013). Another idea is that frontal theta acts as an action monitoring signal (Cavanagh et al, 2012; Narayanan et al., 2013; Laubach et al., 2015), which can be generated through simple recurrent spiking network models (Bekolay et al., 2014). Finally, instead representing a specific function, frontal theta may act as a convenient "language" for distant brain regions to exchange information with each other (Womelsdorf et al., 2010). Our general findings contribute to this literature by suggesting that frontal theta acts as a value signal to guide consummatory behavior, which is the ultimate consequence of many goal-directed actions in natural environments.

A Common Code for Reward Magnitude

A major finding in the present study (Figures 1 and 2) was the similar electro-physiological signals in MFC and OFC are associated with the consumption of high and low concentration liquid sucrose rewards and large and small volume rewards. Although other studies have found either decreases (Kaplan et al., 2001) or increases in behavior with increases in concentration and volume rewards in the same study (Hulse et al., 1960; Collier and Myers, 1961; Collier and Wills, 1961), these studies did not investigate the electrophysiological correlates of consuming rewards. Our study is the first to show a generalized "value signal" in the frontal cortex that scales with increased size and increased concentration of liquid sucrose. These signals might underlie the computation of a common currency (Montague and Berns, 2005; Levy and Glimcher, 2011; Levy and Glimcher, 2012;

525 Strait et al., 2014) for the amount of nutrient available in a given food item and contribute to
526 value-guided control of consumption.

527 *Evidence for the Contextual Control of Consumption*

528 In the Blocked-Interleaved Task (Figure 3A), rats who licked more, longer, and faster
529 for the high concentration reward when rewards were blocked did not continue to do so during
530 interleaved portion of the task (Figure 3B-C). Instead, they licked nearly equally for the high and
531 low concentration solutions, a result that is suggestive of the loss of positive contrast effects for
532 the higher value fluid that is commonly found in the blocked design (Parent et al., 2015a).
533 Despite these differences in behavior, the rats' LFPs in MFC and OFC showed high levels of
534 lick-entrained activity, essentially equal to that found during consumption of the higher value
535 fluid in the blocked part of the session. This finding is hard to reconcile with enhanced lick
536 entrainment reflecting reward contrast effects. If positive contrast engenders entrainment, then
537 LFPs should have shown reduced phase locking to the lick cycle in the interleaved portion of the
538 task. Instead, the results might suggest that LFPs in MFC and OFC are entrained to licking
539 when rats engage in persistent licking, as was found in the periods with high concentration
540 access in the blocked part of the sessions and across the entire interleaved part of the session,
541 and entrainment is reduced when rats switch to sampling the fluid during periods with low value
542 access in the blocked part of the session. By this view, LFP entrainment to the lick cycle could
543 serve as a contextual marker for reward state and the behavioral strategy deployed by the rat to
544 sample and wait or persistently consume the liquid sucrose. This contextual information would
545 depend on knowledge of the temporal structure of the reward deliveries. That is, when reward
546 values are blocked, the rats have learned to expect alternative access to higher and lower
547 reward values over extended periods of time (30 sec). By contrast, when reward values are

548 interleaved, the changes in values occur rapidly and are unpredictable. The reduction in lick
549 entrainment might therefore reflect the animal's sampling strategy.

550 Contextual coding of reward value was also apparent in the Three Reward Task
551 (Figures 6-8), where lick entrainment was stronger when the higher value option was available
552 (Figure 7). In this case, the strength of engagement, for MFC but not OFC, tracked reward value
553 in an absolute manner, with entrainment being higher for the 16% sucrose solution compared to
554 the 8% solution when both were the "best" option (Figure 8C,D). These electrophysiological
555 results were notably distinct from behavioral measures such as total licking output and lick rate
556 (Figure 8A,B), which provided evidence for relative value comparisons. Our electrophysiological
557 results support theories of absolute reward value (Hull, 1943; Spence, 1956; Flaherty, 1982), as
558 opposed to theories of relative reward value (Crespi, 1942; Black, 1968; Webber et al., 2015).
559 Our findings might also fit with the neuro-economics idea of menu invariance versus menu-
560 dependent goods (Padoa-Schioppa, 2011), both of which have been supported by
561 electrophysiological studies on OFC (Padoa-Schioppa and Assad, 2006; Padoa-Schioppa and
562 Assad, 2008; Tremblay and Schultz, 1999; Saez et al., 2017).

563 It is not clear from our studies if the reduction in entrainment when low value rewards
564 are available is an active or passive process. For example, it is possible that some active input
565 to the MFC and OFC denotes the temporal context (e.g. dopamine, hippocampus) and
566 enhances entrainment when the higher value option is available. Alternatively, signals from
567 sensorimotor regions of the frontal cortex, which sit in between the MFC and OFC, the oral
568 sensory and motor cortices (Yoshida et al., 2009), might be reduced during periods with less
569 intense licking, leading to a passive reduction in overall frontal lick entrainment. Future studies
570 are needed to address these neural mechanisms of licking-related synchrony in the rodent
571 frontal cortex.

572 *Subtle Differences between MFC and OFC*

573 MFC and OFC are ideal locations for representing several aspects of value-based
574 decision making, since the cortical regions receives sensory input, project to motor planning
575 areas, and are connected with dopamine-rich areas either directly or through the striatum
576 (Sugrue et al., 2005). Both OFC and MFC play a role in processing and evaluating rewards, and
577 show activity modulated around the receipt and consumption of reward as well as the execution
578 of rewarding behaviors. These areas may be contributing to value-based decision making in a
579 goal-directed system (Balleine and Dickinson, 1998; Rangel et al., 2008; Rangel, 2013), where
580 the value of a given reward is computed, and information about previous outcomes can be used
581 to update values of predicted future outcomes (i.e., predicted rewards). This idea agrees with
582 our findings of increased theta phase-locking in MFC and OFC LFPs during licks for the high
583 value rewards, whether that reward is sweeter or larger in volume, which can be viewed as
584 subjective value.

585 The electrophysiological results from the Blocked-Interleaved Task and Three Reward
586 Task suggest that MFC and OFC, while showing similar results overall, may be contributing to
587 processing reward information in different ways. In accord with a previous theory on proposed
588 MFC and OFC functions (Balleine and Dickinson, 1998, Balleine and Dickinson, 2000;
589 Schoenbaum et al., 2009; Sul et al., 2011; Passingham and Wise, 2012), MFC activity may be
590 acting to maintain and optimize licking behavior in an action-centric manner, as reflected in
591 measures such as the licking rate, a measure associated with vigor. By contrast, OFC activity
592 generally reflected differences in reward value, perhaps due to the different sensory properties
593 of the fluids (Gutierrez et al., 2006), and was not sensitive to licking rate (vigor) or task
594 engagement (total licks).

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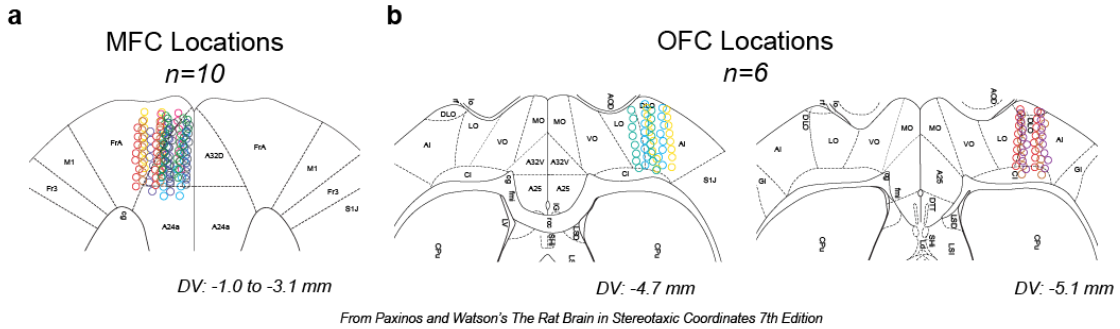
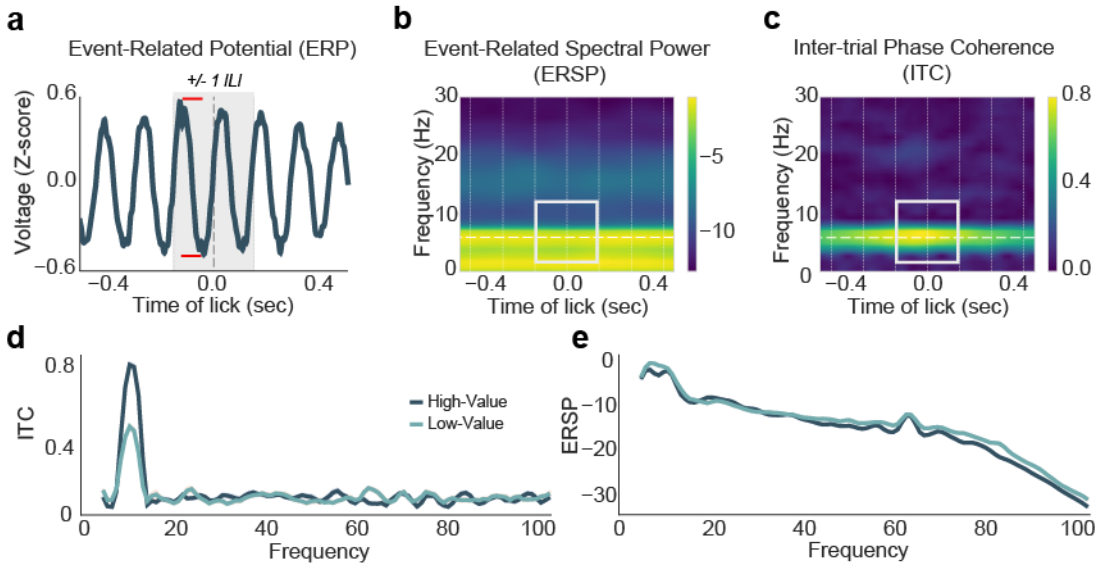
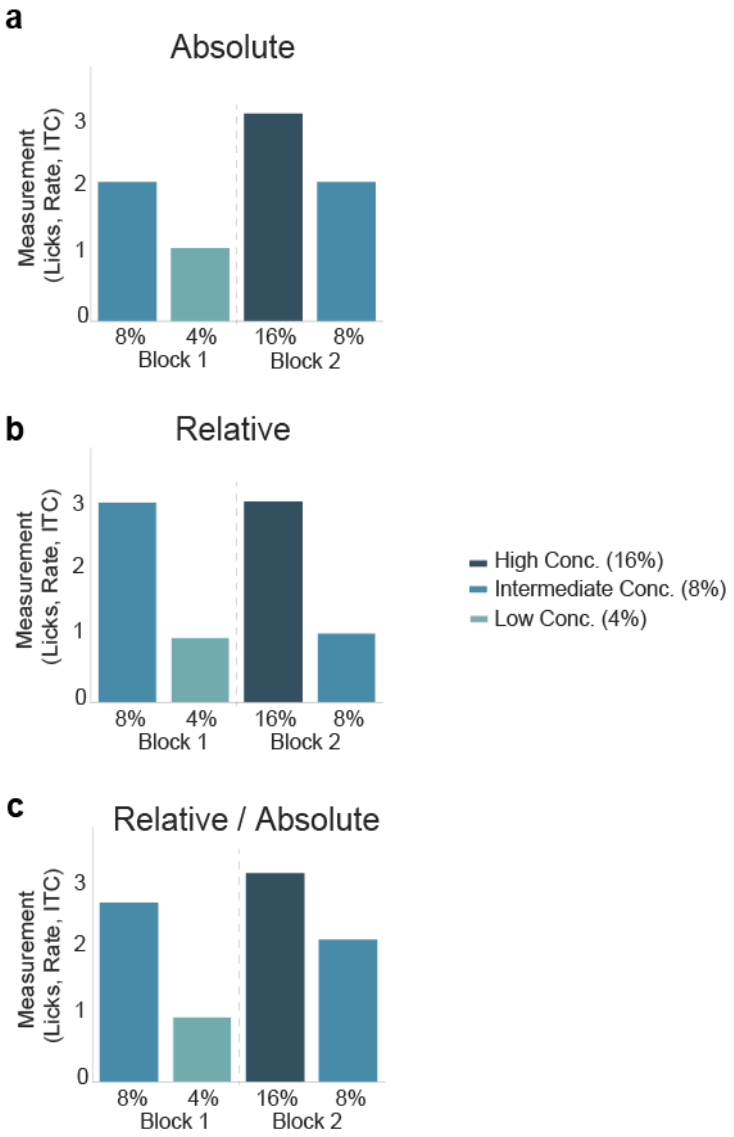


Supplementary Figure 1. Electrode localization. Locations of all electrodes plotted. A. MFC (n=10 rats; 160 electrodes) electrode arrays were localized around area 32 (A32D) and M2 (FrA) from 1 to 3 mm ventral from the brain's surface. B. OFC (n=6 rats; 96 electrodes) electrode arrays were localized around agranular insular (AI) and lateral orbital (LO) areas of OFC from 4.7 to 5.1 mm ventral from the brain's surface. Reconstructions were plotted over atlas figures from Paxinos and Watson's The Rat Brain in Stereotaxic Coordinates, 7th edition (2013).

Supplementary Figures



Supplementary Figure 2. Types of Electrophysiological Measures Used to Assess LFP Activity Related to Behavior. A. Event-related potentials (ERPs) were recorded around licks (time 0) after LFP activity was filtered and z-scored. Peak-to-peak analysis was performed on the ERP centered around each lick with a +1 inter-lick interval (ILI) window to calculate the amplitude size (red limits = maximum minus the minimum amplitude of the ERP). B,C. Spectral measures of power (B) and phase (C). Grouped statistics were based on the mean maximum Event-Related Spectral Power (ERSP) and Inter-Trial phase Coherence (ITC) value from 2-2 Hz and around +1 ILI (grey window). Vertical lines denote the rat's average ILIs. Horizontal line denotes the rat's median lick rate. D. Maximum ITC values over frequencies from 0-100 Hz from all 16 MFC electrodes from one example rat. E. Maximum ERSP measures over frequencies from 0-100 Hz in all 16 MFC electrodes from one example rat.



Supplementary Figure 3. Hypothesis for Relative versus Absolute Encoding of Reward Value. A. If rewards are processed in an absolute manner, we expected to see a graded expression (in lick counts, lick rate, bout duration, or ITC values) of reward value where the high (16%) concentration reward expression is greatest, followed by equal expression of the intermediate (8%) reward and then low expression of the low (4%) concentration reward. B. If rewards are processed in a relative manner, we expected to see a comparative process of rewards, where the “high value” (8% in block 1 or 16% in block 2) are processed similarly, and the focus is on the comparison within each block or context. C. An alternative hypothesis which incorporates a combination of relative and absolute processing of reward value, with partially mixed results of each process in A and B.