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Exploring the Neural Mechanisms Behind Social Decision-Making, Cooperation, and Aggression

Diverse brain areas implicated in a variety of social behaviors

WASHINGTON, DC — Humans, primates, and many other animals are innately social, spending much of their lifetimes in the presence of other individuals, but little is known about the neural mechanisms that generate social behaviors. Recent advances offer insight into neural circuits and mechanisms that underlie social decision-making, cooperation, and aggression. The studies are being presented at Neuroscience 2017, the annual meeting of the Society for Neuroscience and the world's largest source of emerging news about brain science and health.

The neurobiology of social behaviors can be challenging to study partly due to the difficulty of recording brain activity in behaving animals. Advances in the design and durability of devices for recording brain activity have now enabled the targeted study of discrete brain structures during social behaviors, revealing the activation of a wide array of neural circuits during social interactions with other individuals.

Today's new findings show that:

- Stimulation of the CA2 region of the hippocampus, the brain's memory center, may drive aggression in mice, suggesting a means whereby social memory can control social aggression (Félix Leroy, abstract 426.03, see attached summary).
- Neuronal activity in the primate amygdala can predict choices made by a partner, suggesting the brain area plays a role in observational learning and social decision-making (Fabian Grabenhorst, abstract 789.06, see attached summary).
- Primate brain activity during a cooperative game implicates strategic thinking rather than empathy in social decision-making (Wei Song Ong, abstract 251.02, see attached summary).
- Neural activity in the primary motor cortices of two monkeys can become highly synchronized during a social task, carrying information about the task as well as the proximity of the two animals (Miguel Nicolelis, abstract 777.12, see attached summary).

"In the past, studies focused on brain lesions or pharmacological manipulations that affected an animal with respect to its social interaction toward others," said press conference moderator Robert Greene, a professor in the departments of Neuroscience and Psychiatry at the University of Texas Southwestern Medical Center. "We now see evidence of shared and interactive neuronal activity between social partners that extends to such things as cooperative behavior and learning and decision-making."

This research was supported by national funding agencies such as the National Institutes of Health, as well as other public, private, and philanthropic organizations worldwide. Find out more about the neuroscience of social behavior on *BrainFacts.org*.

Related Neuroscience 2017 Presentation

Minisymposium: Big News From a Little Region: Hippocampal Area CA2
Sunday, Nov. 12, 8:30–11 a.m., WCC Ballroom C

Abstract 426.03 Summary

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Hippocampal Region May Help Promote Aggressive Behavior in Mice

Finding suggests new role for the brain's memory center in regulating social aggression

A region of the hippocampus, the brain's memory center, may be involved in promoting aggression, suggesting a link between social memory and social aggression, two behaviors that are dysregulated in a variety of neuropsychiatric disorders, according to new animal research released today at Neuroscience 2017, the annual meeting of the Society for Neuroscience and the world's largest source of emerging news about brain science and health.

The hippocampus plays an important role in learning and memory, and different parts of the hippocampus communicate with numerous brain regions involved in a wide range of functions and behaviors. To explore the hippocampal networks involved in social behavior, researchers used transgenic mice to study neural connections projecting from a region of the hippocampus known as CA2 to the lateral septum, a brain area implicated in the modulation of aggression.

Stimulation of projections from CA2 to the lateral septum released an inhibitory "brake" on an aggression brain circuit in the hypothalamus, the "primal" part of the brain that controls basic motivated behaviors such as mating and feeding. The researchers also found evidence that vasopressin, a hormone involved in pair-bonding and other social behaviors, may promote aggression via the CA2-lateral septum circuit.

The team then used a genetically-encoded sensor of neural activity in awake, active animals to assess the importance of social interactions for this brain network. "When social exploration was happening, there was no activity whatsoever," said lead author Félix Leroy, an associate research scientist at Columbia University. "The second that aggression started is when the projection turned on really strongly. We're now trying to look at the exact relay of signals in these brain regions to confirm that this burst of activity precedes aggression."

Research was supported with funds from the National Institute of Mental Health.

Scientific Presentation: Monday, Nov. 13, 3–4 p.m., WCC Halls A–C

2307. CA2 circuits controlling social behaviors
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TECHNICAL ABSTRACT: The hippocampal CA2 area lodged between CA3 and CA1 integrates inputs from the entorhinal cortex, the dentate gyrus, CA3 as well as the supramammillary nucleus, the medial septum and the raphe. Its output remains, however, poorly understood. We characterized strong CA2 projections to the ventral CA1 area (vCA1) and the lateral septum (LS) and have been probing their respective behavioral function by silencing each set of terminals. CA2 and vCA1 were recently shown to be necessary for social memory. We find that dorsal CA2 projects to and excites ventral CA1, providing a potential social memory circuit. We further find that dorsal CA2 excites dorsal LS (dLS). Moreover this projection is not involved in social memory but acts to enhance social aggression through a disinhibitory circuit: CA2 excites dLS, which inhibits ventral lateral septum (vLS), thereby relieving tonic inhibition of the aggression-promoting hypothalamic VMHvl area. This is agreement with studies showing that deletion of the arginine vasopressin 1b receptor (AVPR1b), which is highly enriched in CA2, reduces social aggression. Our results show that activation of AVPR1b on CA2 presynaptic terminals enhances CA2-LS excitatory synaptic transmission and that selective blockade of these receptors inhibits social aggression. Although it remains unclear how CA2 outputs and their modulations by vasopressin control different social behaviors, our study, together with previous results, suggests a close relationship between social memory and aggression. We are currently investigating the behavioral effect of silencing the CA2-vCA1 projection to explore whether differential neuromodulation of divergent projections from a single brain region may selectively recruit memory versus aggressive social behaviors.

Abstract 789.06 Summary

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Neuronal Activity in Primate Amygdala Predicts Choices Made By a Social Partner

Research implicates brain region in learning from social observations

Neuronal activity in the primate amygdala can mirror and even predict reward-seeking choices made by a partner animal, according to new research released today at Neuroscience 2017, the annual meeting of the Society for Neuroscience and the world's largest source of emerging news about brain science and health. The results suggest a specific role for the amygdala in mediating complex social behaviors.

The amygdala is well known for its role in identifying faces and facial expressions related to emotion. To assess the amygdala's role in social learning, researchers recorded the activity of individual neurons in two monkeys during a learning task. The monkeys took turns choosing among images on a touch screen that were associated with different amounts of a juice reward. Because each monkey could observe the choices made by its partner, it could learn the reward values of specific images from both its own trial-and-error choices and those of its partner.

As the learning task progressed, neurons in the amygdala of one monkey began to signal the reward values of choices made by the partner monkey. Crucially, this learning occurred via observation alone, even when the monkey had not itself interacted with those images. Eventually, these neurons transitioned to activity that predicted the partner monkey's next choice. This shift in the amygdala's neuronal activity was previously only observed during an individual's own learning of a task.

"Taken together, our results suggest that amygdala neurons may simulate the decision processes of social partners during observational learning," said lead author Fabian Grabenhorst, PhD, a research fellow at the University of Cambridge. "We are currently building a biologically-inspired computer model of the amygdala's decision circuits based on our findings. Such a model might help us to understand how the different kinds of neuronal signals may interact during observational learning and decision-making, as well as the consequences of specific dysfunctions of different neuron types in this system," which may underlie cognitive disorders seen in conditions such as autism.

Research was supported with funds from the Wellcome Trust, the National Institutes of Health Caltech Conte Center for Neuroscience, and the European Research Council.

Scientific Presentation: Wednesday, Nov. 15, 2–3 p.m., WCC Halls A–C

4710. Primate amygdala neurons simulate decision processes of social partners

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TECHNICAL ABSTRACT: The amygdala has long been implicated in social behavior. Yet, the contributions of primate amygdala neurons to social functions remain unclear. Here we examined amygdala neurons as monkeys made value-based decisions in a social setting that allowed them to observe and learn from each other's behavioral choices and reward outcomes. Two monkeys faced each other over a touch screen and alternated making choices between sequentially presented visual objects. Choices were based on learned reward probabilities that changed over trial blocks. Each animal worked on its own choice objects before objects switched between animals to test observational learning. Of 205 recorded amygdala neurons, 59 neurons (29%) signalled reward values of specific visual objects that evolved over trial blocks, irrespective of which monkey was choosing the object and irrespective of whether value derived from own experience or observation. Critically, amygdala object value signals emerged during observation even before the recorded monkey experienced reward from that object. Population decoding indicated that neuronal values derived from observation benefitted subsequent performance: when object value was decoded with higher accuracy during observation, the recorded monkey required fewer trials to learning criterion when making subsequent choices involving that object. Beyond valuation, functionally related neurons predicted the object choices of the recorded monkey and partner monkey (73/205 neurons, 35%). Some of these neurons exclusively predicted the partner's choices, suggesting a specific 'simulated' choice signal rather than generalized choice prediction. Amygdala neurons showed dynamic coding transitions within trials: initial object-value signals frequently developed into choice-predictive signals. Such value-to-choice transitions constitute a neuronal signature of decision-making predicted on computational grounds that was previously observed in amygdala neurons in non-social, economic decisions (Grabenhorst et al., 2012). Our data suggest that amygdala neurons derive object values from observational learning and simulate the decision computations of social partners. The findings link traditional concepts of amygdala social functions with recent concepts of amygdala decision functions. The data also inform theories of social learning by suggesting that learning from the behaviour of others is a constructive process that involves simulation of social partners' decision computations. Grabenhorst, F., Hernadi, I., and Schultz, W. (2012). Prediction of economic choice by primate amygdala neurons. Proc Natl Acad Sci U S A 109, 18950-18955.

Abstract 251.02 Summary

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Strategic Thinking, Not Empathy, May Underlie Cooperative Behavior in Primates

Brain region responds to live monkey partner, not computer player, in cooperative decision-making game

Engaging in a cooperative decision-making game with a live partner, but not a computer or decoy, activates neural circuitry implicated in strategic thinking in rhesus macaques, according to new research presented today at Neuroscience 2017, the annual meeting of the Society for Neuroscience and the world's largest source of emerging news about brain science and health. The finding suggests that strategic thinking, rather than empathy, may be a primary driver of cooperative social behavior.

To explore the neural basis of cooperation, which is not well understood, researchers trained two monkeys to engage in a simulated game of "chicken," in which the combined decisions of the players determined each player's reward. The monkeys drove simulated cars straight toward each other (risking a collision) or veered sideways (avoiding a collision), and they could see both their opponent's face and their opponent's choice to go straight or veer. During the game, researchers measured neural activity in brain regions implicated in empathy and in strategic thinking.

The monkeys altered their choices based on the relative rewards of risking a collision, veering while the opponent went straight, or cooperatively veering. In general, dominant monkeys were more willing to risk a collision for a reward, while submissive monkeys required a much higher reward to risk a collision. In some trials, one opponent was replaced with a decoy or a computer, and these cases were more likely to result in collisions. The researchers found that cells in a brain region linked to strategic thinking activated during cooperation with another live monkey.

"We found that neurons in a part of the brain linked to strategic thinking, but not in a part of the brain linked to empathy and shared experience, respond selectively when rhesus macaques cooperate with a live partner, but not a decoy or a computer," said lead author Wei Song Ong, PhD, a postdoctoral scholar at the University of Pennsylvania. "These findings highlight the role of strategic thinking in social decisions." The researchers next plan to probe how activity in these brain regions influences different types of strategic behavior.

Research was supported with funds from the National Institute of Mental Health and the Simons Foundation Autism Research Initiative.

Scientific Presentation: Sunday, Nov. 12, 2–3 p.m., WCC Halls A–C

5877. Neural mechanisms mediating cooperation
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TECHNICAL ABSTRACT: We hypothesize that cooperation results from the interaction of neural circuits mediating reward, empathy and theory of mind. fMRI studies in humans have shown that the anterior cingulate cortex (ACC) and temporal parietal junction (TPJ) are activated by vicarious reward and mentalizing respectively. These are two functions that conceivably contribute to cooperation, yet the precise neural processes remain unknown. To address this gap, we developed a new task based on the classic "chicken game". Two monkeys (M1&M2) face each other across a shared screen showing 2 colored annuli framing dot motion arrays and 4 response targets. On some trials, the larger reward (denoted by visual tokens) lies opposite M1 behind the opponent (M2)'s annulus; smaller rewards lie to the left (see figure). To obtain the larger reward, M1 goes straight, but if M2 also goes straight the annuli collide and neither monkey gets reward. On some trials, a "cooperation bar" allows both monkeys to obtain larger rewards if and only if both choose to go left; if only one yields he receives a smaller reward. Dot motion coherence is randomized on some trials to obscure intention signals. Our 4 trained monkeys maximized juice intake by attending to the reward tokens as well as the choices of their opponent. Monkeys' strategies depended on their opponent. Dominant monkeys preferentially aggressed and required more incentive to cooperate, while subordinates preferentially yielded. Collisions were more frequent when a computer player replayed prior live monkey trials in the presence of a 'decoy' monkey, compared with playing a computer in the absence of a decoy monkey or playing an active monkey. Players quickly initiated cooperation for small rewards with an active player, and distinguished between active players and decoys within 15 trials. To determine the neuronal basis of these behaviors, we recorded the spiking activity of 535 neurons from ACC and 449 from the putative monkey TPJ in the middle STS (mTPJ). Neurons in both areas are sensitive to cued payoffs, decisions, and explicit signaling of intentions in different opponent conditions. Our key finding is that 53% of neurons in mTPJ differentially respond to the same amount of juice when obtained through a cooperative act compared with obtaining it selfishly. Provocatively, this was true only when monkeys played a live opponent. These findings demonstrate that neurons in mTPJ respond differentially to the presence and behavior of (non-) interactive agents, suggesting it plays a role in the integration of social cues, actions, and outcomes to guide strategic social decisions.

Abstract 777.12 Summary

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Simultaneous Neural Recordings From Two Interacting Primates Show Synchronized Activity in Motor Cortex
Brain-to-brain synchronization may represent neural correlate of social behavior

By simultaneously recording neural activity from two primates, researchers show monkeys can develop matched patterns of brain activity in the motor cortex during social interactions, according to new research released today at Neuroscience 2017, the annual meeting of the Society for Neuroscience and the world's largest source of emerging news about brain science and health.

Studies in primates have long suggested that activity in different parts of the brain "mirrors" the observed behavior of other individuals. However, previous work has relied on general measures of brain activity or neural recordings from only a single animal of an interacting pair. To correlate cortical activity with a social behavior, researchers simultaneously measured activity in the primary motor cortex (M1) of two monkeys while the animals participated in a social task. One monkey, the passenger, sat in a motorized wheelchair that was driven in a path around a room toward a fruit reward. Another monkey, the observer, sat in a chair in the corner of the same room with a clear view of the passenger and received a juice reward each time the passenger received fruit.

Initially, the wheelchair's trajectory toward the fruit was dictated by a computer. During these passive trials, activity in M1 of both monkeys became highly synchronized, with up to 70 percent of neural units firing at the same time. Synchronized activity carried information about the location and velocity of the wheelchair, as well as the distances from the passenger to the fruit and to the observer. Next, using a brain-machine interface, the wheelchair's path was determined by combined M1 activity from both monkeys. The more synchronized the M1 activity of the two animals, the more efficiently the monkeys could cooperatively lead the wheelchair to the reward. Notably, the monkeys' successful use of M1 activity to guide the wheelchair did not require any physical movements of their bodies.

"This synchronous activity could predict not only the movements of the wheelchair, but could also could predict the distance between the two monkeys," said senior author Miguel Nicolelis, MD, PhD, founder of Duke University's Center for Neuroengineering. "Our results suggest that even the primary cortical areas, very basic areas like the motor cortex, always function in terms of a social context." The researchers next intend to record from three or four monkeys simultaneously during an elaborate motor task to see whether such synchronization can occur across multiple individuals.

Research was supported with funds from the National Institute of Neurological Disorders and Stroke and The Hartwell Foundation.

Scientific Presentation: Wednesday, Nov. 15, 4–5 p.m., WCC Halls A–C

12567. Brain-to-brain synchronization between monkey pairs during whole-body navigation
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TECHNICAL ABSTRACT: While it is well known that the behavior of primates is principally social, neurophysiological mechanisms of social interactions in primates are not well understood. For example, primary motor cortex (M1) has been long researched as an area that controls limb motion, whereas its possible role in social behavior has not been considered. Here we show that M1 neuronal ensembles represent both the parameters of whole-body movements and social interaction of two monkeys placed in the same room. Moreover, we show that brain-to-brain synchronization is a neuronal correlate of social interactions. The experiments were conducted in three monkeys chronically implanted with cortical multielectrode arrays. A pair of monkeys participated in each experiment. One monkey, called observer, sat in a stationary chair placed in the corner of the room, where it had a full vision of the second monkey, called passenger. The passenger's chair was mounted on a motorized wheelchair that navigated in the room. In passive-navigation trials, the wheelchair moved along computer-generated trajectories toward a fruit dispenser. When the passenger arrived at the dispenser location, it grasped a piece of fruit, and juice was given to the observer monkey. Simultaneous, wireless recordings from M1 ensembles in both monkeys showed that both the passenger's and observer's neurons represented wheelchair motion and location, as well as the distance from the passenger to the reward and from the passenger to the observer. An ensemble correlation analysis revealed significant brain-to-brain synchronization that depended on the navigation parameters. The brain-to-brain correlation increased when the passenger approached the fruit dispenser or to the observer. We took advantage of this synchronization to build a Brainet, where two monkeys' brains controlled the wheelchair movements conjointly. In the Brainet trials, both the passenger's and the observer's M1 activity contributed to the wheelchair movements. In the successful trials, where the monkeys guided the wheelchair to the target before the 2-minute timeout, brain-to-brain correlation was higher compared to the failure trials. These results suggest that (1) M1 neuronal ensembles track both the self-motion and motion of other members of the group, (2) brain-to-brain synchronization encodes social interactions, and (3) Brainets based on such synchronization can enable cooperative tasks.