Neural mechanisms of social decision-making in the primate amygdala

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Social decisions require evaluation of costs and benefits to oneself and others. Long associated with emotion and vigilance, the amygdala has recently been implicated in both decision-making and social behavior. The amygdala signals reward and punishment, as well as facial expressions and the gaze of others. Amygdala damage impairs social interactions, and the social neuropeptide oxytocin (OT) influences human social decisions, in part, by altering amygdala function. Here we show in monkeys playing a modified dictator game, in which one individual can donate or withhold rewards from another, that basolateral amygdala (BLA) neurons signaled social preferences both across trials and across days. BLA neurons mirrored the value of rewards delivered to self and others when monkeys were free to choose but not when the computer made choices for them. We also found that focal infusion of OT unilaterally into BLA weakly but significantly increased both the frequency of prosocial decisions and attention to recipients for context-specific prosocial decisions, endorsing the hypothesis that OT regulates social behavior, in part, via amygdala neuromodulation. Our findings demonstrate both neurophysiological and neuroendocrinological connections between primate amygdala and social decisions.

amygdala | social decision | value mirroring | oxytocin | hierarchical modeling

How we treat others impacts not only their well-being but our own. Human society depends on cooperation, charity, and altruism, as well as institutions to regulate selfish biases. In humans, these behaviors involve perspective-taking, empathy, and theory of mind (1, 2), and the rudiments of these capacities appear to mediate complex social behavior in animals (3). Recent research has sketched a rough outline of the neural circuits that contribute to complex social behavior (4, 5). These comprise a set of domain-general brain areas, including the ventromedial prefrontal cortex and ventral striatum, that process information about reward and punishment and contribute to decision-making, and a set of specialized areas, including the temporoparietal junction and medial prefrontal cortex, that process specifically social information (4, 6). How social and nonsocial signals in these circuits are integrated to mediate decisions with respect to others remains imperfectly understood, in part, due to the indirect nature of hemodynamic signals measured in human neuroimaging experiments that constitute the bulk of this research. Recent advances in the development of neurophysiological and neuropharmacological models of social decision-making, however, permit more direct inquiry into the neural mechanisms mediating other-regarding behavior (7–11).

The amygdala, especially the basolateral division (BLA), has been implicated in both decision-making and social perception, inviting the possibility that it contributes to decision-making with respect to others (12–17). This set of nuclei is well known for contributions to emotional experience and expression, especially fear. More recent studies demonstrate activity in BLA tracks the value of rewards and punishments (18), predicts risky financial decisions (19), reflects internal motivational goals (20), and correlates with vigilance and attention (21). BLA also signals social information, such as facial expressions and the direction of gaze, and has been implicated in theory of mind and emotional empathy (22–26). Notably, oxytocin (OT), a neurohypophysial hormone that modulates many social behaviors (27), appears to do so via the amygdala in humans and nonhuman primates (28–30). Intranasal OT reliably modulates hemodynamic activity in the amygdala in healthy humans (28, 29, 31), children with autism (32), and rhesus macaques (30). These changes in amygdala activity are related to social cognition. These observations invite the hypothesis that BLA directly mediates decision-making with respect to others (24). How neurons in BLA respond during social decisions, however, remains unknown.

Here, we examine this hypothesis using a modified dictator game, which we previously used to probe social information signaling by neurons in the anterior cingulate and orbitofrontal cortices (7) and the impact of inhaling OT on social decision-making (33). We previously reported that the preference to allocate reward to the other monkey is enhanced by greater familiarity between the two animals, and is abolished if the recipient is replaced with a juice collection bottle (34). We also reported that reward withholding is reduced when actor monkeys are dominant toward recipients, and the variability and the degree of preferences often depend on the identity of the recipients (34). We show, to our knowledge for the first time, that BLA neurons respond during social decisions, these responses signal the value of rewards chosen for self and others using a similar coding scheme, and these signals are correlated with social preferences. We further show that unilateral infusion of OT

Significance

Making social decisions requires evaluation of benefits and costs to self and others. Long associated with emotion and vigilance, neurons in primate amygdala also signal reward and punishment as well as information about the faces and eyes of others. Here we show that neurons in the basolateral amygdala signal the value of rewards for self and others when monkeys make social decisions. These value-mirroring neurons reflected monkeys' tendency to make prosocial decisions on a momentary as well as long-term basis. We also found that delivering the social peptide oxytocin into basolateral amygdala enhances both prosocial tendencies and attention to the recipients of prosocial decisions. Our findings endorse the amygdala as a critical neural nexus regulating social decisions.

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into BLA increases both the frequency of prosocial decisions and attention paid to the recipients of prosocial decisions. Together, these findings directly implicate the amygdala in social decision-making and constrain models of its computational role in the decision process.

Results

To test the role of the primate amygdala in decision-making with respect to others, we recorded extracellular activity from 150 BLA neurons while rhesus macaques (*Macaca mulatta*) made decisions resulting in juice rewards to self, a recipient monkey present in the same room, both animals, or neither (7, 33, 34) (Fig. 1 *A*–*D*).

Summary of Behavior. Prosocial behavior is defined as voluntary behavior that benefits another individual, and includes helping, sharing, donating, and cooperation (35–37). Consistent with prior studies (7, 33, 34), monkeys strongly preferred to deliver rewards to the recipient (*Other*) over no one (*Neither*), a prosocial preference (Fig. 1*E*; Fig. S1). By contrast, monkeys preferred to deliver rewards to themselves (*Self*) over both themselves and the recipient (*Both*), possibly reflecting the tendency for monkeys to compete for fluids in the home colony (7, 33, 34). Preference for *Self* over *Both* but *Other* over *Neither* militates against the possibility that actors' choices merely reflect the visual and auditory salience of another monkey drinking juice. Our prior findings that actors are more prosocial toward both more familiar and socially subordinate

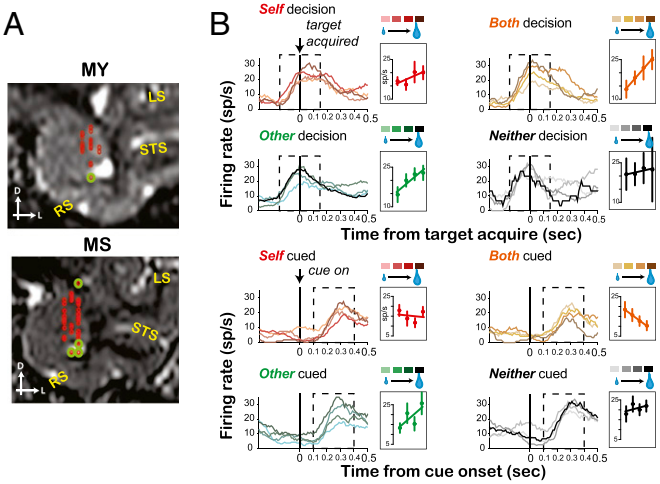

Fig. 2. Neuronal activity in BLA. (*A*) Recording sites from MY and MS projected onto representative slices ($n = 75$ each from MY and MS). The locations with green circles show the locations that appear outside of BLA on these representative slices. (*B*, *Upper*) Peristimulus time histograms (PSTHs) of the neuronal activity (sp/s) of a single BLA neuron aligned to target acquire. (*Lower*) PSTHs of the same neuron on cued trials, aligned on the time of cue onset. On cued trials, the reward value scaling was not grouped by whether a live agent received the reward or not (only significant for *Both*-cued and *Other*-cued activity and in opposite directions; both $P < 0.02$).

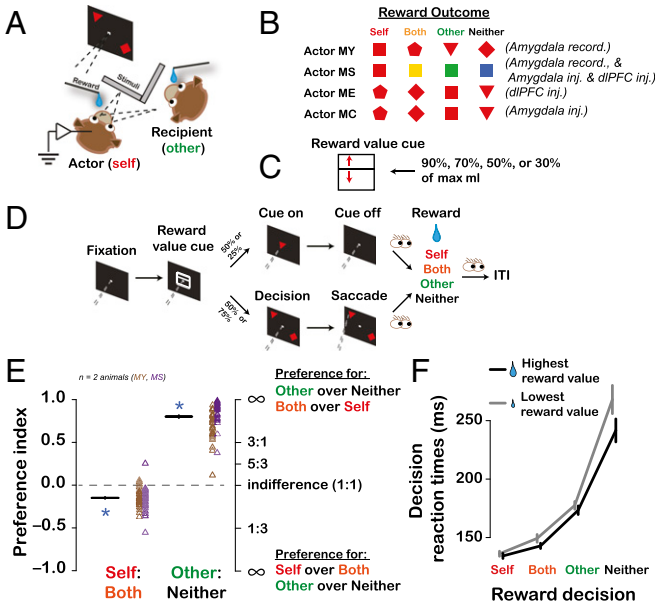

Fig. 1. Experimental setup and behavior. (*A*) Experimental setup. (*B*) Stimulus–reward outcome mappings for reward delivered to actor (*Self*), recipient (*Other*), both (*Both*), or no one (*Neither*). (*C*) Reward value cue used to indicate juice amount at stake for each trial (*D*). The position of the horizontal bisecting line (red arrow) specified one of the four percentages of maximum reward. (*D*) Task structure for decision and cued trials. Dashed gray lines show the angle of the actor's gaze. Eye cartoons indicate times at which the actor could look around without any task demand. ITI, intertrial interval. (*E*) Behavioral preferences index [mean (horizontal lines) ± SEM (vertical lines) across two actor animals] as a function of reward outcome contrasts. Data points show the biases for individual sessions separately color-coded for MY and MS. The actors strongly preferred *Other* over *Neither* decision, but preferred *Self* over *Both* decision (asterisks; both $P < 0.0001$, one-sample t test, $n = 150$). MY and MS showed a comparable antisocial preference in the *Self* vs. *Both* trials ($P = 0.34$, t test), whereas MS showed stronger prosocial preference in the *Other* vs. *Neither* trials ($P < 0.0001$). (*F*) Decision RTs (mean of session medians ± SEM) differed across decision types [$F_{(3,1052)} = 175.95$, $P < 0.0001$] and reward value [highest vs. lowest, $F_{(1,1052)} = 5.79$, $P = 0.02$].

recipients (34), as in humans (38), and show no preferences when the recipient is replaced by a juice collection bottle, validates our task as an assay of social decision-making. Actors often looked at the recipient after making a decision (Fig. S2), consistent with vicarious reinforcement (34), a process mediating empathy (39). Actors looked at the recipient more often after delivering higher-value rewards compared with lower-value rewards (Fig. S2). Finally, decision reaction times (RTs) varied with both who was chosen to receive the reward and its magnitude (Fig. 1*F*).

Value-Mirroring by BLA Neurons. We explored how BLA neurons encode the value of rewards for another individual compared with how they encode the value of rewards for oneself (Fig. 2*A*). Fig. 2*B* shows an example neuron with activity aligned to the time of decision. This neuron increased firing when the actor monkey made a decision in all contexts. Surprisingly, when we separated neuronal activity by reward value, we found a key difference between conditions in which a live agent was chosen as the recipient of reward (*Self*, *Other*, *Both*) and those in which no live agent received a reward (*Neither*). Mean firing rates scaled positively with reward value similarly across *Self*, *Both*, and *Other* decisions (all $P < 0.03$, bootstrap test) but not for *Neither* decisions ($P = 0.27$). By contrast, we did not observe common reward tuning on cued trials, when actors could not choose whom to reward (Fig. 2*B*). Notably, this neuron showed different value tuning profiles in decision and cued trials (compare in Fig. 2*B*, *Upper* and *Lower*), suggesting that value coding depends on whether the monkey uses the information to guide action.

To quantify how BLA neurons encode reward value for self and others, we used a GLM with reward value (30%, 50%, 70%, and 90%) and trial type (decision and cued) for trials resulting in *Self*, *Both*, *Other*, *or Neither* reward outcomes. Across all 150 cells, 18% of neurons showed significant ($P < 0.05$, permutation test) value tuning for *Self*, 25% for *Other*, 16% for *Both*, and 18% for *Neither* rewards. The percentages of neurons showing either positive or negative tuning were comparable across all reward types (all comparisons, $P > 0.09$, single-sample proportion test; Fig. 3*A*), similar to what has been reported previously in BLA (40). We found significant correlations for reward sensitivities

(β) between *Self* reward and *Both* reward ($r = 0.36$, $P < 0.001$, Pearson's correlation; Fig. 3*B*), which is perhaps not surprising given that the actor monkey received a reward in both conditions. Remarkably, reward value sensitivities for *Self* and *Other* ($r = 0.22$, $P = 0.01$) and for *Other* and *Both* were also strongly and positively correlated with one another ($r = 0.38$, $P < 0.001$; Fig. 3*B*), despite the fact that actors received rewards following *Self* or *Both* decisions but not following *Other* decisions. There were also significant but negative correlations between *Self* and *Neither* reward value sensitivities ($r = -0.21$, $P = 0.02$) and *Both* and *Neither* reward value sensitivities ($r = -0.21$, $P = 0.029$), potentially reflecting an opponent coding scheme for received (*Self* and *Both*) and discarded (*Neither*) rewards. *Other* and *Neither* reward value sensitivities were not correlated ($r = -0.06$, $P = 0.55$), despite the fact that these outcomes were both associated with the actor receiving no reward.

Correlated reward value coding may be driven simply by the salience of juice delivery itself. However, we found no correlations for value tuning between decision trials and cued trials for any of the reward outcomes, an operational control for the salience of observable visual and auditory consequences of juice delivery to the actor, recipient, or both monkeys (all $r < 0.15$, $P > 0.12$, Pearson's correlation; Fig. 3*C*). Likewise, none of the correlations were significant during the cue offset epoch on cued trials (i.e., an analogous epoch to the target acquisition epoch on decision trials; Fig. S3). We next tested whether value- mirroring

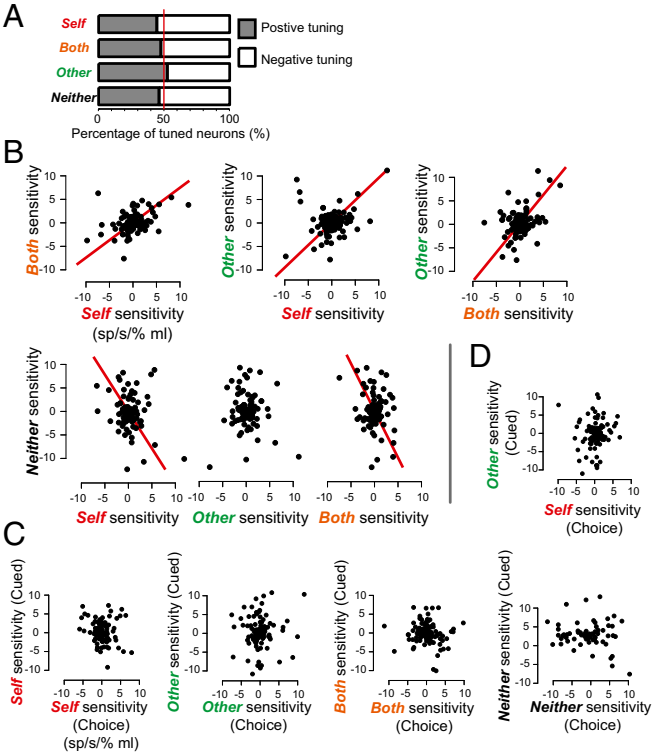

Fig. 3. The population of BLA neurons commonly signals the values associated with rewards chosen for self and others. (*A*) Proportions of BLA neurons that are either positively or negatively tuned to increasing reward values collapsed across decision contexts. (*B*) Reward value sensitivities (changes in the firing rates per changes in the proportion of juice amounts at stake; sp/s/% max mL) are plotted for different reward outcomes. (*C*) Reward value sensitivities are plotted for decision and cued trials within each reward outcome separately for decision and cued trials. In both *B* and *C*, the solid red lines through the data points show significant linear regressions in each monkey. (*D*) Reward value sensitivities for *Self* decision trials are plotted against those for *Other* cued trials (same format as in *B* and *C*).

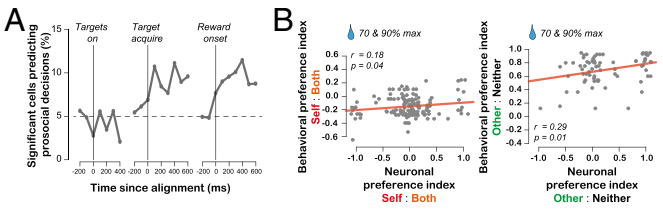

Fig. 4. Neuronal activity in BLA is correlated with social decisions. (*A*) Time course of decision signaling, with activity separately aligned to the onset of targets (*Left*), the acquisition of a choice target (*Center*), and the onset of reward (*Right*). Results stem from a sliding-window logistic regression against the type of decision for that trial. Prosocial decisions were those resulting in *Other* or *Both* rewards, and antisocial decisions were those resulting in *Self* or *Neither* rewards. Plotted are the percent of neurons for which the decision term in the regression reached statistical significance for each 400-ms window centered on the time point indicated in the abscissa. (*B*) The relationship between the behavioral preference indices and the neuronal preference indices. Each data point represents the neuronal preference index of a neuron and the behavioral preference index from the session in which the neuronal data were collected. Shown are the two high reward value conditions (70%, 90% of max mL) for *Self:Both* (*Left*) and *Other:Neither* (*Right*) decisions. Data points that lie precisely at the extremities (−1 and 1) are jittered for the display. Outcomes of a linear regression are indicated on the plots.

is specific to decisions by examining the correlation between value sensitivities on *Self* decision and *Other* cued trials (Fig. 3*C*). Value sensitivities were correlated on *Self* decision and *Other* decision trials (statistics above; Fig. 3*B*) but not on *Self* decision and *Other* cued trials ($r = 0.09$, $P = 0.36$; Fig. 3*D*). The specificity of value mirroring for decision trials (also see the single neuron example in Fig. 2*B*) further militates against the notion that common value representations in BLA are entirely driven by the salience of reward delivery itself or sensory feedback from juice consumption by the actor or recipient. Instead, our findings indicate that value mirroring in BLA requires motivation and active task engagement associated with making decisions.

To examine the time course of correlations between value sensitivities for different reward outcomes, we performed an additional GLM from different epochs within a trial, separately for each trial type (Fig. S3). The target acquisition epoch reflected value mirroring more clearly than other epochs. Value-mirroring signals in BLA thus occur on a time scale consistent with the process of commitment to a decision or forecasting its outcome.

If BLA contributes to social decisions by computing reward values for self and others using a common coding scheme, then BLA activity should be correlated with prosocial decisions. We constructed a running logistic regression over time based on spike counts to see whether we could detect whether monkeys would make or made prosocial decisions (*Both or Other*) combined across the two decision contexts (*Materials and Methods*). At target onset, the relationship between spiking activity and the likelihood of making a prosocial decision remained at chance (Fig. 4*A*). By contrast, from the time immediately following the decision to well after the delivery of reward, the activity of more neurons than would be predicted by chance signaled the likelihood of making a prosocial decision ($P < 0.001$, single-sample proportion test; Fig. 4*A*). These analyses show that a subset of BLA neurons with value-mirroring activity signal prosocial decisions on a local time scale. However, when we repeated the same analysis for each context separately, the proportion of neurons with significant correlations did not reach significance for either context for any period, possibly due to insufficient statistical power.

To test whether BLA signals were also correlated with longer-term social preferences, we examined the relationship between session-to-session decision indices and similar indices constructed from neuronal firing rates across sessions (*Materials and Methods*). We found that BLA neuron activity was significantly, albeit

weakly, correlated with prosocial tendencies for *Self and Both* decisions at all reward values (high value: $r = 0.18$, $P = 0.04$; low value: $r = 0.17$, $P = 0.04$, Pearson's correlation; Fig. 4*B*; Fig. S4) as well as for *Other* and *Neither* decisions at high reward values ($r = 0.29$, $P = 0.01$; Fig. 4*B*) but not low-reward values ($r = 0.19$, $P = 0.12$; Fig. S4). Thus, neuronal activity in a subset of BLA neurons (more in Figs. S5 and S6) is correlated with social decisions at both short and long timescales.

To properly move from characterization of individual neurons to population inferences, we make use of a hierarchical Bayesian approach. Hierarchical models have the advantage of "borrowing" statistical strength across units, both regularizing fits in cases of limited data and leading to robust inferences of population statistics. Moreover, by treating both population and individual variability within a single Bayesian model, we avoid problems with multiple comparisons and a proliferation of models fit to subsets of the data. Our modeling results recapitulate and strengthen our findings, endorsing the same conclusions made from characterizing individual neurons more directly (Figs. S7–S9).

Unilateral OT Infusion into BLA Increases Prosocial Decisions. OT is a well-known modulator of social behavior, and several imaging studies in humans and monkeys have implicated the amygdala in this process (28–31, 41–45). Inhaled OT increases OT concentration in the central nervous system and enhances both prosocial preferences and social attention in rhesus macaques (33). Recently, it has been demonstrated that OT administration modulates hemodynamic activity in the amygdala in rhesus macaques (30), and it has been hypothesized that the primate amygdala may express presynaptic OT receptors (46). If reward value-mirroring by the amygdala is critical for prosocial behavior, we reasoned that directly increasing OT levels in the amygdala would increase the likelihood that monkeys would make prosocial decisions.

To test this hypothesis, we focally and unilaterally injected OT (2 μL, 5 ng/nL) or saline (2 μL, vehicle) into locations in BLA where we had observed value-mirroring activity (*Materials and Methods* and Fig. 5). As a control, we focally injected OT or saline into the dorsolateral prefrontal cortex (dlPFC) (Fig. 5), a cortical area in which OT receptors have not been localized in macaques. Relative to vehicle, OT infusion into BLA, but not dlPFC, increased the frequency of prosocial decisions [treatment: BLA, $F_{(1,24)} = 4.44$, $P < 0.05$; dlPFC, $F_{(1,20)} = 0.01$, $P = 0.92$]. Because the effects of OT injection into BLA were mainly observed in the first half of the session (median ± SD trial duration: 54 ± 12 min; Fig. 5*A*), we focus on the 30-min time window beginning 5 min into the completion of each injection hereafter [first 30 min: BLA, $F_{(1,24)} = 4.77$, $P = 0.04$ vs. after 30 min: $F_{(1,24)} = 0.02$, $P = 0.88$; dlPFC, $F_{(1,20)} = 0.01$, $P = 0.93$ vs. $F_{(1,18)} = 0.43$, $P = 0.52$]. Crucially, there was no interaction between treatment and monkey [treatment × subject: $F_{(1,24)} = 1.61$, $P = 0.22$], although we did not have enough power to detect significance in each monkey separately [four sessions each; treatment: MS: $F_{(1,12)} = 4.08$, $P = 0.07$; MC: $F_{(1,12)} = 0.78$, $P = 0.40$]. We did not see any significant changes in prosocial decision-making following OT injections into dlPFC (Fig. 5*A*). For both BLA and dlPFC injections, we did not find significant effects when each reward context was considered independently [BLA treatment: $F_{(1,12)} = 2.95$, $P = 0.11$ for *Self:Both*, $F_{(1,12)} = 2.00$, $P = 0.18$ for *Other:Neither*; dlPFC treatment: $F_{(1,10)} = 0.20$, $P = 0.67$ for *Self:Both* and for *Other:Neither*]. We also found no reward context interaction in either BLA or dlPFC [treatment × context: $F_{(1,24)}$, $F_{(1,20)} < 0.71$, $P > 0.41$].

Our prior studies found that systemic OT inhalation increases social gaze as well (33). Here, unilateral OT injection into BLA did not directly enhance overall social gaze (Fig. 5*B*) [treatment: $F_{(1,24)} = 0.20$, $P = 0.66$; treatment × subject: $F_{(1,24)} = 3.73$, $P = 0.07$]. Likewise, OT injections into dlPFC did not evoke any effects on social gaze [treatment: $F_{(1,20)} = 0.11$, $P = 0.75$; treatment × subject: $F_{(1,20)} = 0.04$, $P = 0.85$] (Fig. 5*B*, *Right*). Neither did we find any significant effects on social gaze when each reward context was considered independently [BLA treatment: $F_{(1,12)} < 0.43$, $P > 0.52$ for *Self:Both* and *Other:Neither*; dlPFC treatment: $F_{(1,10)} < 0.15$, $P > 0.71$ for *Self:Both* and *Other:Neither*] nor any reward context interaction in either BLA or dlPFC [treatment × context: $F_{(1,24)}$, $F_{(1,20)} < 0.62$, $P > 0.44$].

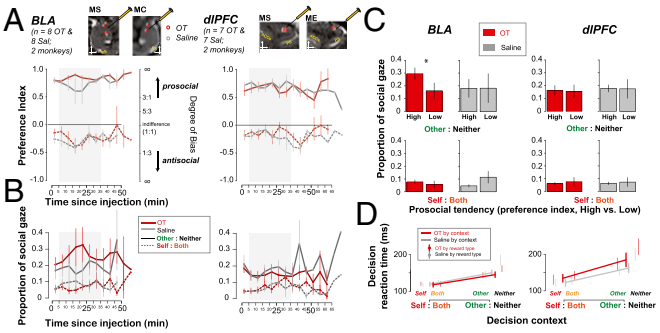

Fig. 5. Infusing OT into the value-mirroring sites in BLA promotes prosocial decisions. (*Upper*) Projected injection sites for OT (red) and saline (gray) (jittered for visibility). (*A*) The time courses of social preference index (mean ± SEM) in 5-min bins following the local infusion of OT (red) or saline (gray) into BLA (*Left*) or dlPFC (*Right*). The solid and dashed lines show *Other:Neither* context and *Self:Both* context, respectively. The shaded region shows the 30-min window. (*B*) The time courses of social gaze (proportions per session in mean ± SEM) following the infusion of OT or saline into BLA or dlPFC. Same format as in *A*. (*C*) Proportion of social gaze as a function of high vs. low prosocial sessions (median split on the preference indices) for BLA OT, BLA saline, dlPFC OT, and dlPFC saline injection. Asterisk indicates a significant modulatory relationship among BLA OT injection, high vs. low prosocial preferences, and corresponding social gaze proportions. (*D*) Decision RTs (mean of the session medians ± SEM) following OT or saline into BLA or dlPFC. Also shown are the individual RT means with SEM across individual decision types.

In prior work, we found that actors were more likely to look at recipients after making a prosocial choice (7, 33, 34), inviting the possibility that OT injections into BLA may influence social gaze indirectly by altering social preferences. To test this idea, we performed a median-split analysis by segregating days associated with stronger vs. weaker prosocial preferences and then examined the frequency of social gaze separately for each dataset. On those days when actors expressed stronger prosocial preferences on *Other:Neither* trials following OT injections into BLA, they were also more likely to look at the recipient ($P = 0.02$, permutation test; Fig. 5*C*). We did not observe this relationship on *Self:Both* trials following OT injections into BLA, nor any effects on *Other:Neither* or *Self:Both* trials following OT injections into dlPFC (all $P > 0.22$, Fig. 5*C*). Thus, OT injections into BLA selectively enhanced social gaze when these injections were more effective at promoting prosocial behavior, potentially reflecting better signaling of neurons expressing OT receptors or more reliable receptor binding (47).

Finally, OT injections into both BLA and dlPFC did not alter decision RTs [treatment: $F_{(1,24)}$, $F_{(1,20)} < 1.99$, $P > 0.17$; treatment × subject: $F_{(1,24)}$, $F_{(1,20)} < 1.37$, $P > 0.26$] (Fig. 5*D*), suggesting that the behavioral effects of OT are not simply driven by enhanced arousal or salience. Although the effects were small following our unilateral injections, our findings invite the hypothesis that OT enhances prosocial behavior, as well as social attention, in part, by modulating the activity of BLA neurons that encode the value of rewards chosen for self and others.

Discussion

The concept of action-mirroring has been hypothesized to be central to social cognition (48), and neurons specialized for action mirroring have been described in parietal and premotor cortices (49). Our findings demonstrate that neurons in BLA

mirror the value of rewards for self and others and, moreover, these signals are correlated with prosocial decisions, thus extending the concept of mirroring to social decision-making. Using the same paradigm, we previously showed that neurons in the anterior cingulate gyrus (ACCg) respond when actor monkeys choose to reward both self and others (7). Although the responses of ACCg neurons predict how prosocial an animal is across sessions, they do not signal the value of rewards chosen for self and others (7). Distinct social reward signals observed in ACCg and BLA suggest different, potentially hierarchically layered, computational roles for these areas. One possibility is that ACCg may compute signals relevant for assigning credit or agency to the recipients of rewards (50) or shared experience (51, 52), whereas the amygdala may compute reward prediction or outcome signals relevant for making decisions (53, 54) or learning (18, 55).

Importantly, value-mirroring was not observed when the same rewards were delivered to actor or recipient by a computer, in the absence of active decisions; it was also not observed when actors chose not to distribute reward to a live agent (*Neither* condition). Such value-mirroring for decisions that only impact live social agents has interesting implications. Neurons in BLA appear to categorize social events as similar as long as there is a live agent involved (*Self*, *Other*, or *Both*), and do so only during active decision-making, with all its attendant motivational, emotional, and attentional components (17, 21, 24, 56, 57). The amygdala has been implicated in the integration of motivation and emotion (12), and our findings suggest contexts in which a live social agent is relevant engage these integrative processes. The integration of emotional and motivational signals during social interactions may serve to compute signals representing the value of rewards for self and others using a common scaling function observed here.

BLA has elaborate and reciprocal connections with prefrontal cortex (58) and projects to the nucleus accumbens in the ventral striatum (59, 60), endorsing a role for the amygdala in shaping how these circuits process the value of rewards during decision-making. We speculate that mirroring of reward values for self and others by BLA serves to adjust the gain of neuronal signals mediating social decisions in the brain. Grouping reward values for self and others in a common currency might be fundamental to empathic understanding of the experiences of others—whether they are cooperators, defectors, donors, or beneficiaries—and may underlie the capacity for the richness of social behaviors expressed in humans and other primates.

Numerous studies have found that inhaling OT alters hemodynamic activity in the human amygdala (28, 29, 31), but no prior studies have demonstrated that OT-selective processing within the amygdala actively promotes prosocial behavior in human or nonhuman primates. Here we found that unilateral infusion of OT into sites in BLA where value-mirroring neuronal activity was observed weakly but significantly modulates prosocial behavior, but that OT injections in dlPFC do not. Notably, when OT infusion was more effective at promoting prosocial behavior it also increased attention to the recipient of prosocial choices, thus implicating value-mirroring by BLA neurons in social attention as well as social reward. Understanding how OT alters the activity of value-mirroring neurons during ongoing social behavior may reveal a source of individual differences in OT-mediated social behaviors such as empathy and social gaze, with important implications for use of OT as treatments for disorders like autism and schizophrenia, in which these functions are compromised.

Value-mirroring may be an efficient means of computing information about the experiences of others using a neural code built on self-experience. Despite this computational efficiency, however, mirroring generates information that is fundamentally ambiguous with respect to agency. Nevertheless, this coding scheme may offer advantages as well. The combination of neurons that signal information about self and others on a common scale and neurons that differentially signal self- or other-specific information (7–9, 11) may implement a highly sophisticated mechanism both for distinguishing agency and conveying information about others from the perspective of oneself. The presence of value-mirroring activity in the primate amygdala is particularly noteworthy given that this set of nuclei is a key node for signaling emotional experience (21). Value-mirroring by BLA neurons thus may be a core mechanism subserving emotional empathy. By contrast, social reward neurons in ACCg (a part of the medial prefrontal network) that encode the reward outcome experienced by others (either exclusively or concurrently with self-rewards) (7) may be specialized for mediating cognitive empathy or theory of mind (22, 61, 62).

Materials and Methods

General and Behavioral Procedures. All procedures were approved by the Duke University Institutional Animal Care and Use Committee and were conducted in compliance with the Public Health Service's Guide for the Care and Use of Laboratory Animals. See *SI Materials and Methods* for the details on behavioral, recording, and microinjection procedures.

Data Analysis. See *SI Materials and Methods* for the behavioral analyses. We computed spike rates associated with each decision during the 300-ms window centered around the time of decision registration (i.e., target acquisition) on decision trials. We computed cue-related spike rates during the 300-ms window (from 100 to 400 ms relative to cue onset). The time course of BLA population around the time of decisions, separately by enhanced and suppressed cell types, is shown in Fig. S5. For the analyses aligned on target onset (for both decision and cued trials), we used the epoch between 50 and 150 ms from the target onset. Finally, we calculated spike rates during the reward epoch from 50 to 400 ms relative to the onset of reward delivery. We used the spike rates from these epochs for all of our GLM-based analyses (see below). We also computed spike rates used for social gaze analysis from 50 to 450 ms aligned to the time of social gaze detection (i.e., eye positions entered into the social gaze window) during either the prereward epoch or postreward epoch. To isolate social gaze-related activity during the postreward epoch, we subtracted the activity leading up to 250 ms before the time of the gaze from the activity associated after the social gaze. The time course of an example BLA neuron around the time of social gaze, as well as the comparisons of gaze-related activity across different reward outcomes in individual cells, are shown in Fig. S6.

We defined a value sensitivity of firing rates to different reward values for each reward outcome as a change in firing rates as a function of different reward values (i.e., slope, sp/s/% max) in each neuron. Overall, a total of 100 cells (67%) and 102 cells (68%) showed value-dependent modulations in any of decision and cued trials, respectively, with a minimum of 55% of variance-explained (r^2, linear regression) for at least one decision or cue type being considered.

We generated three separate GLM (Eq. **1**) of firing rate, based on Poisson distribution using a log link function (denoted as $Firing\ Rate_{poisson}$). To compare across reward outcomes, we fit models for each reward outcome (*Self*, *Both*, *Other*, and *Neither*) individually. The full GLM examined the variance in firing rates due to the type of trial (decision or cued) and the reward size (expressed as percentages of the maximum reward value; 30–90%).

$$Firing\ Rate(i)_{poisson} = \beta_0 + \beta_1 * (Reward\ Size) + \beta_2 * (Trial\ Type) \quad [1]$$

β_1 and β_2 signify the coefficients for reward size and trial type, and β_0 signifies a constant or noise term. Each neuron was considered separately. We used the built-in MATLAB function glmfit with settings for a Poisson distribution and a log link function. Firing rates were drawn from a 300-ms time window centered on the time in which information about the reward outcome was first signaled. We then correlated the reward-size β-values (β_1) of each neuron across reward outcomes (Fig. 3*B*). The statistics reported in Results were based on a Pearson's correlation. However, because these β-values depend on firing rate, we then carried out a type-II linear regression to construct the regression line (gmregress in MATLAB). We generated a second GLM (Eq. **2**) to compare responses to increasing reward sizes depending on the type of trial (decision or cued) within reward outcomes (Fig. 3*C*).

$$Firing\ Rate(i)_{poisson} = \beta_0 + \beta_1 * (Reward\ Size) \quad [2]$$

β_1 signifies the coefficients for reward size and β_0 a constant or noise term. Each neuron was considered separately. The firing rate data, including the time windows used, were also identical to that of the first GLM. Within each reward outcome, we then correlated the reward size β-values (β_1) between trial types.

This GLM was also used for examining the correlations across different epochs separately for trial types. The procedure was identical to that of the second GLM, except that additional epochs of firing-rate data were considered.

We carried out a logistic regression to test the ability of neurons to discriminate between prosocial (*Both* or *Other*) and antisocial (*Self* or *Neither*) decisions (Fig. 4*A*). To examine the time course, we obtained spike counts using 400-ms sliding windows, with a step size of 100 ms. Given that there are variable delays between task events on each trial, we used three separate alignments of activity: target onset, target acquisition, and reward delivery onset. For each alignment and for each neuron, we assigned *Both* rewards and *Other* rewards to 1 (prosocial), and *Self* rewards and *Neither* rewards to 0 (antisocial), and then regressed these values within each time window using glmfit with settings for a binomial distribution and a logit link function. Within each time window, we then calculated the percent of fitted neurons for which the decision term was significant ($P < 0.05$).

To test the effect of injecting OT or saline into either BLA or dlPFC, we carried out an analysis of variance, with treatment (OT or saline), context (*Self:Both* or *Other:Neither*), and subjects [MS or (ME or MC)] as factors.

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