Reward: From Basic Reinforcers to Anticipation of Social Cues

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Abstract Reward processing plays a major role in goal-directed behavior and motivation. On the neural level, it is mediated by a complex network of brain structures called the dopaminergic reward system. In the last decade, neuroscientific researchers have become increasingly interested in aspects of social interaction that are experienced as rewarding. Recent neuroimaging studies have provided evidence that the reward system mediates the processing of social stimuli in a manner analogous to nonsocial rewards and thus motivates social behavior. In this context, the neuropeptide oxytocin is assumed to play a key role by activating dopaminergic reward pathways in response to social cues, inducing the rewarding quality of social interactions. Alterations in the dopaminergic reward system have been found in several psychiatric disorders that are accompanied by social interaction and motivation problems, for example autism, attention deficit/hyperactivity disorder, addiction disorders, and schizophrenia.

Keywords Reward system · Anticipation · Social reward · Dopamine · Nucleus accumbens · Oxytocin · Autism · ADHD · Addiction · Schizophrenia

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1   Introduction

Rewards play a crucial part in almost all aspects of life and form the basis for goal-directed behavior and motivation. For example, the rewarding nature of food and sex assures survival and reproduction, the expectation of money and status drives many humans to work hard, and the desire for social relatedness and affiliation guides our behaviors during social interactions. Rewards such as food are called 'primary reinforcers' as they satisfy basic needs and do not require learning of the reinforcing value. In contrast, 'secondary reinforcers' such as money acquire their rewarding value by learned associations with primary reinforcers. Generally, two temporally distinct phases of reward processing need to be considered: an anticipatory phase and a consummatory phase. During reward anticipation, incentive salience is attributed to reward-predictive cues, rendering the stimulus a desirable goal and inducing approach behavior, whereas reward consumption is characterized by hedonic reactions to the pleasure gained by the reward (Berridge and Robinson 1998).

1.1   The Dopaminergic Reward System

On the neural level, reward processing is mediated by a number of different brain regions. At the heart of this complex network is a cortical–basal ganglia circuit comprising the ventral striatum (in particular the nucleus accumbens), orbital prefrontal cortex, anterior cingulate cortex, ventral pallidum, and the midbrain dopamine neurons in the ventral tegmental area (VTA) and substantia nigra (SN) (Haber and Knutson 2010). Dopamine projections from the VTA to the nucleus accumbens (NAcc, see Fig. 1), the so-called mesolimbic pathway, are considered the most important pathway for reward learning, anticipation, and approach behavior.
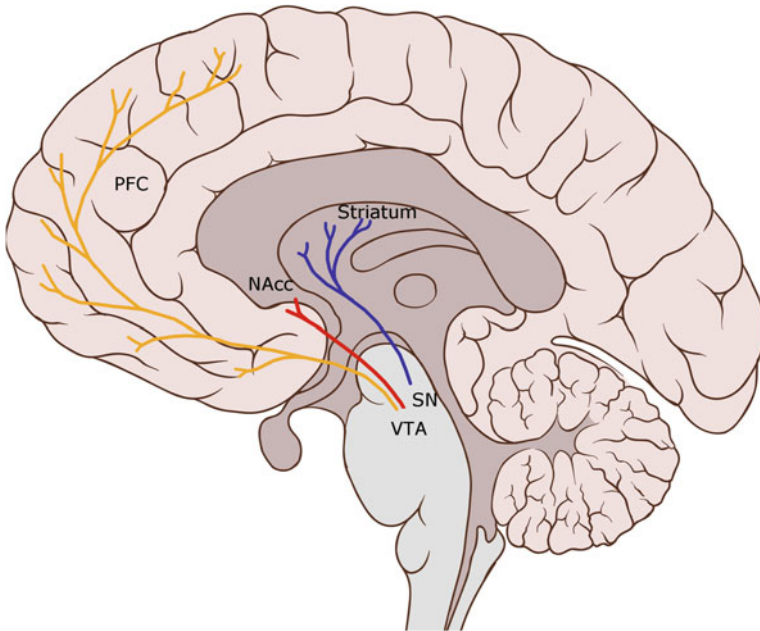
Fig. 1 Dopaminergic pathways in the human brain. The mesolimbic (*red*) and mesocortical (*orange*) pathways begin in the ventral tegmental area (VTA) and project to the nucleus accumbens (NAcc) and prefrontal cortex (PFC). The nigrostriatal pathway (*blue*) transmits dopamine from the substantia nigra (SN) to the dorsal striatum. See URL: https://commons.wikimedia.org/wiki/File:Brain_human_sagittal_section.svg

Electrophysiological studies in monkeys and other mammals (Mirenowicz and Schultz 1996) have demonstrated that midbrain dopamine neurons in the VTA and SN (as well as neurons in their projection sites at the striatum, frontal cortex, and amygdala) encode reward prediction error signals. That is, they show phasic activations in response to unpredicted and novel rewards. However, if the reward is contingently preceded by a predictive cue, the firing responses to reward consumption fade away and shift toward the predictive cue, reflecting reward anticipation. If an expected reward is omitted, neuronal firing is further suppressed, encoding a negative prediction error. Further research showed that such dopamine-related firing in the midbrain can also encode magnitude, probability, and temporal delay of rewards (Schultz 2013).

Most of the knowledge about dopaminergic reward processing is based on animal research, but recently there have been a few pioneering studies exploring reward responses at the single neuron level in humans (e.g., Zaghloul et al. 2009; Lega et al. 2011). For example, neuronal activity was recorded during reward-related tasks in the SN of Parkinson patients and in the NAcc of individuals with major depression and obsessive–compulsive disorder who underwent deep brain stimulation surgery. In line with the animal data, these studies showed

reward-responsive spike activity of nucleus accumbens and midbrain dopamine neurons. Although it is important to show that the basic principles guiding reward processing in humans are similar to those observed in animals, such studies are limited in their generalizability since patient pathology (in particular related to the dopaminergic circuitry) is an unavoidable confound and research with healthy subjects cannot be carried out for ethical reasons. Therefore, noninvasive imaging techniques such as functional magnetic resonance imaging (fMRI) are typically applied to examine neuronal correlates of reward-related behavior in healthy humans. Although fMRI cannot directly measure neural activity, there is evidence that dopamine release in the NAcc increases the local blood-oxygen-level-dependent (BOLD) signal (Knutson and Gibbs 2007).

1.2 fMRI Studies on Reward Processing

The simplest way to investigate human reward processing is to use experimental designs, which contrast pictures with a positive valuation to those with a neutral, negative, or less positive valuation. In this manner, fMRI studies have used a wide range of primary and secondary rewards such as food, erotic pictures, attractive faces, sports cars, funny cartoons, images of a romantic partner, and visual art (e.g., Stark et al. 2005; Beaver et al. 2006). Other studies use learning paradigms during fMRI to map reward prediction error signals and the acquisition of predictive value of stimuli to their respective brain areas (Daniel and Pollmann 2014).

Another common experimental paradigm to study reward processing using fMRI is the incentive delay task. This paradigm includes explicit cues indicating whether and which reward can be expected, if the participant performs a task correctly (e.g., hitting a button as fast as possible upon the appearance of a target). The incentive delay paradigm is particularly useful to investigate reward anticipation in comparison with reward consumption. In recent years, it has been applied to examine the anticipation of various primary and secondary rewards, for example money, pleasant taste stimuli, smiling faces, erotic pictures, and professional success (e.g., Knutson et al. 2001; Paulus 2015; Spreckelmeyer et al. 2009).

In line with the electrophysiological results, fMRI studies have reported activations in dopamine-innervated brain regions during reinforcement learning and reward processing, in particular the NAcc and orbital prefrontal cortex (see (Liu et al. 2011) for meta-analysis). More specifically, imaging results confirm both the encoding of reward signals *and* reward expectation/anticipation in the human striatum, in prefrontal cortex, and in midbrain nuclei, which is strikingly similar to the firing pattern of dopamine neurons that are observed in animal studies. These findings support the crucial role of the mesocorticolimbic reward circuit for incentive-based learning and reward anticipation. For reward anticipation, nucleus accumbens, medial prefrontal, and orbitofrontal activities have been suggested to represent a 'common currency' for the valuation of different reward types, ranging from primary rewards to more complex and abstract reinforcers. Thus,

mesocorticolimbic activity not only increases proportionally to the magnitude of an expected reward but also represents the relative personal reward value (e.g., Gross et al. 2014; Sescousse et al. 2014).

2 Social Reward

In social psychology, the quest for social acceptance and belonging is considered a basic motive of humans: We have a strong motivation to seek social relationships and enjoy friendship, mutual support, and understanding. On the other hand, social belongingness makes us care for the needs of others and motivates us to act pro-socially. Thus, it seems reasonable to assume that social connectedness and pro-social behavior have a rewarding quality mediated by the mesolimbic reward circuit. In the last decade, neuroscientific researchers have become increasingly interested in the rewarding nature of social interaction (Krach et al. 2010). In this context, the term 'social reward' has been employed for a broad variety of positive social stimuli and experiences, ranging from static pictures of faces to complex social experiences such as cooperation.

2.1 fMRI Studies on Social Reward

Genetic and pharmacological studies have shown that the dopamine system is crucial for social interaction. For example, genes involved in striatal dopamine transmission modulate social approach behavior (Enter et al. 2012) and a pharmacological increase of the dopamine concentration improves learning about a partner's pro-social preferences (Eisenegger et al. 2013). In line with these findings, several functional neuroimaging studies have demonstrated that structures of the dopaminergic reward circuit are activated by social stimuli and experiences.

For instance, data obtained in neuroimaging studies support the view that social belonging, acceptance, and support function as 'social rewards,' confirming social psychological theories: The ventral striatum was found to be activated when subjects feel understood (Morelli et al. 2014) or receive positive feedback about themselves (Izuma et al. 2008) but deactivated during a conflict with the prevailing group opinion (Klucharev et al. 2009). Also, the mere expectation of positive social feedback (e.g., in terms of a smiling face, verbal praise, or liking statements by others) was shown to elicit ventral striatal activity (e.g., Kirsch et al. 2003; Rademacher et al. 2010), reflecting a motivational drive for social approval.

Another type of social interaction experienced as rewarding is mutual support in terms of collaboration. Even toddlers were shown to have a preference to access a reward collaboratively instead of individually (Rekers et al. 2011). Accordingly, fMRI studies in adults have demonstrated that cooperation with an unknown person is associated with activations of the reward network (e.g., the NAcc, ACC,

orbitofrontal and ventromedial prefrontal cortex). However, ventral striatal and ACC (but not OFC) activity is specific to human social interaction and not elicited when cooperating for instance with a computer partner (Rilling et al. 2002). These findings have been interpreted to reflect reward learning in terms of who can be trusted to cooperate, but also the rewarding nature of cooperation and reciprocated favors, which motivates us to act pro-socially and to withstand the temptation of being selfish (Strang and Park 2017).

The assumption that pro-social behavior has an intrinsic motivational value is evidenced by situations where a rewarding experience occurs in the absence of any direct benefit for oneself. For example, imaging studies have shown that donating is associated with activations in structures of the mesolimbic network (ventral striatum, VTA) (e.g., Moll et al. 2006). Moreover, monetary payoffs to charities activate the mesolimbic network in similar ways as monetary rewards to oneself, suggesting that the common neural currency of reward also relates to more complex incentives like the 'joy of giving' and vicarious pleasure (Müller-Pinzler et al. 2017), which make pro-social behavior inherently rewarding. This assumption receives further support from a study that used a gambling task, in which subjects could win rewards either for themselves or for another person (Braams et al. 2014): Anticipatory ventral striatal activity was equally strong when subjects played for the best friend and when they played for their own benefit. However, the social relationship with the others plays an important role: Anticipatory activity was found to be decreased when playing for an unknown or a disliked other person (e.g., Braams et al. 2014). Hence, the intrinsic motivational value of pro-social behavior and vicarious reward anticipation vary with social distance. This is in line with data showing that subjective feelings of excitement and ventral striatal activity when receiving rewards together with another person depend on the social distance of this person (Fareri et al. 2012).

These findings point to a complex involvement of the dopaminergic reward system in social interaction, which is presumably modulated by other neurotransmitters involved in social behavior, for example the neuropeptide oxytocin.

2.2   Oxytocin, Dopamine, and Social Behavior

Oxytocin is known to influence social behavior. It has been found to play a role in pair bonding, sexual behavior, and parenting in different species—also in humans. An increasing number of studies in humans also report an involvement of oxytocin in higher-order social behavior. For example, there is evidence that oxytocin increases emotion recognition, morality, altruism, trust, and generosity, but also ethnocentrism (preferring to help and support the in-group) (see Evans et al. (2013) for review). The underlying mechanisms of these effects of oxytocin are not yet fully understood, but there is some evidence indicating that the dopaminergic reward system plays an important role. A first important hint is the high density of oxytocin receptors in brain regions that are also rich in dopamine receptors like the amygdala, the NAcc, and the VTA (Skuse and Gallagher 2009). Second, an

interaction of these two neurotransmitters has been observed. The effect of intra-nasally administered oxytocin on the amygdala's response to social stimuli has been reported to be modulated by the availability of dopamine (Sauer et al. 2013). Furthermore, animal studies have demonstrated that oxytocinergic circuits and the mesocorticolimbic dopamine pathway are directly connected and the strength of this connection is related to maternal caregiving behavior. Infusions of oxytocin in the VTA result in increased dopamine release within the ventral striatum along with increased maternal behaviors, whereas the injection of an oxytocin antagonist results in the opposite behavior of maternal neglect (Strathearn 2011).

These findings have led to the assumption that an interaction of oxytocin with dopamine regulates socio-affiliative behaviors. Social interaction may be rewarding because oxytocin activates the dopaminergic reward system in response to social cues. There are a few fMRI studies in humans that support this assumption. An intranasal application of oxytocin was found to increase the BOLD response of the VTA to cues signaling social reward or social punishment, which might indicate that oxytocin modulates social behavior by attaching motivational salience to socially relevant cues through mesolimbic dopamine projections (Groppe et al. 2013). Further studies could show that oxytocin facilitates learning with social (rewarding and punishing) feedback and increases the VTA response of female subjects to infant and sexual images as well as VTA and NAcc responses of male subjects to their female partners (e.g., Scheele et al. 2013; Gregory et al. 2015).

So far, these studies support the hypothesis of an interaction of oxytocin with dopamine. More research is needed to shed more light on this interaction and to clarify whether it is the underlying mechanism that makes social interaction rewarding and worth to seek. Other studies, however, have linked oxytocin administration to different emotion processing systems. For example, oxytocin modulates amygdala reactivity in response to threatening stimuli which may result in anxiolytic effects. Thus, the effect of oxytocin is likely not restricted to the dopaminergic system. Future studies will need to address in more detail to what extent the modulation of the dopaminergic system may contribute to the effects of oxytocin for social behavior.

3 Clinical Relevance

3.1 Autism

Autism spectrum disorder (ASD) is characterized by substantial impairments in social interaction and communication, as well as repetitive behaviors and restricted interests. Several recent theorists have focused on reduced social motivation for reciprocal social behaviors to explain deficits in the domain of social interaction and communication. An early lack of interest and pleasure with respect to social encounters may result in cascading negative consequences such as decreased expertise in faces, voices, and ultimately social cognition and behavior (e.g.,

Chevallier et al. 2012). Consequently, research into the behavioral and neural consequences of altered reward processing in ASD has received growing interest in recent years. The results from behavioral studies targeting the social motivation hypothesis are mixed. Several studies confirm a general decrease in sensitivity to social reinforcement in comparison with other reinforcers, or a failure to improve performance under social motivation conditions. Other studies revealed no differences or very subtle effects between social and nonsocial conditions. On the neural level, several studies have demonstrated a domain-general dysfunction of the reward system in ASD that does not seem to be restricted to social stimuli (e.g., Kohls et al. 2013), comprising diverse areas typically associated with reward processing (including the striatum). Other studies have found differences associated with the type of reward, for example more pronounced hypoactivations for social reward conditions (Scott-Van Zeeland et al. 2010) in comparison with monetary reward or differences only for social but not for nonsocial conditions (Delmonte et al. 2012). Interestingly, reward stimuli that are associated with specific restricted interests reliably engage reward circuitry also in ASD (Dichter and Adolphs 2012). To summarize, these results suggest that the brain circuitry mediating dopaminergic reward processing and reinforcement learning may remain functional in ASD, but engagement of the system is highly dependent on the individual motivational value of the employed reward stimuli.

This conclusion is well in accordance with clinical observations. The most effective early behavioral interventions in autism typically use reinforcement-based learning to shape behavior (e.g., applied behavior analysis (ABA)), and an essential part of such interventions is giving salient, frequent positive feedback in response to desired behaviors. Interestingly, this also includes social feedback (such as hugs, smiling, 'thumbs up,' verbal praise), but in a very salient and explicit way. Additional ways of increasing saliency and motivational value of social stimuli thus are a very promising approach for future interventions in ASD. Oxytocin has been shown to modulate the processing of social stimuli (in particular during social reward) and therefore might be a candidate pharmacological agent in this regard (see Sect. 2.2 oxytocin, dopamine and social reward and Poustka and Kamp-Becker 2017). However, the first clinical trials testing the effect of chronic oxytocin administration on the symptomatology of ASD have been somewhat disappointing (see Guastella and Hickie (2015) for review). Future trials are needed to show whether oxytocin proves effective in more targeted approaches—e.g., in combination with specific behavioral strategies or in specific subgroups of patients.

Taken together, it is not clear which aspects of reward processing are particularly impaired in ASD or how these relate to deficits in social motivation and restricted interests, and how they could be most effectively targeted in specific interventions. Results from previous experimental studies are mixed, due to diverse differences with respect to type of employed reward stimuli and behavioral paradigms. In future studies, it would be useful to make use of computational models of reinforcement learning that provide the possibility to tear apart different aspects of dysfunctional reward processing, i.e., impaired reinforcement learning per se, failure to attach motivational value during learning, or diminished reward value of primary and

secondary reinforcers. The few studies employing such a strategy indicate that learning per se might be slower in ASD and particularly impaired for social stimuli, whereas reward value is enhanced for items related to ASD-specific interests. Establishing stable associations via reinforcement learning seems to be more difficult for individuals with ASD who rely more on trial-by-trial updates (Solomon et al. 2015).

3.2 ADHD

Attention deficit/hyperactivity disorder (ADHD) is closely related to dysfunctions of the dopaminergic system. It has been suggested that altered reinforcement mechanisms due to changes in dopamine signaling result in stronger immediate behavioral sensitivity to rewards but at the same time impairments in reward anticipation (Tripp and Wickens 2008). These changes might contribute to poor behavioral control and increased impulsivity typically observed in patients with ADHD. Several behavioral studies have confirmed atypical reward processing in ADHD, including preference for immediate as compared to delayed rewards, enhanced seeking of large but risky rewards, and less behavioral adaptation in response to reward (see Luman et al. 2010 for review). On the neural level, reward anticipation is associated with decreased activation of the ventral striatum in ADHD (Scheres et al. 2007) for both immediate and delayed rewards, whereas ventral striatal and orbitofrontal responses appear to be enhanced during reward outcome (von Rhein et al. 2015). It should be highlighted that the vast majority of studies has focused on monetary reward conditions, but only few studies have investigated social reward in ADHD (e.g., Kohls et al. 2014). These studies suggest a hyper-responsivity when task performance is coupled with social reward in comparison with monetary reward and an associated increase in striatal and medial frontal brain areas. However, more research is needed to elucidate atypical sensitivity for social rewards in ADHD and whether these are evident during processing of reward outcome or reward anticipation.

3.3 Addiction

The dopaminergic reward system plays a crucial role in addictive disorders. All known drugs of abuse acutely increase dopamine release in the nucleus accumbens, but animal studies have shown that dopamine is already released in response to drug-associated cues before the drug administration. Therefore, a sensitization of the reward system is assumed (Robinson and Berridge 2000): Stimuli that were learned to be associated with drug consumption attract attention, become desirable, and motivate drug-taking behavior. In line with this theory, several fMRI studies demonstrated increased striatal activity in smokers and alcoholics during the

presentation of drug-associated pictures (e.g., Wrase et al. 2007). In contrast, other studies which used stimuli not associated with the drug (e.g., monetary rewards) reported decreased ventral striatal activation during reward anticipation (Wrase et al. 2007; Peters et al. 2011). However, not all studies could replicate this finding.

So far, there has been little research on social reward in addiction. There are several observations that suggest an interaction of social reward processing with addictive behavior. First, patients with antisocial behavior disorders have an increased risk for addiction and show an earlier start of consumption and more severe abuse than other substance abusers. Second, social experiences during development strongly affect drug use in later life, social bonds have a protective effect, and social emotions can often be a driver for recovery. In this context, oxytocin appears to have an important role: Exogenous oxytocin administration was found to prevent development of tolerance to several drugs, to inhibit self-administration, and to reduce withdrawal symptoms (McGregor and Bowen 2012). Third, addiction alters social behaviors and is often associated with social dysfunction and isolation. It is assumed that the increased motivation for drugs leads to decreased striving for naturally rewarding stimuli such as social interaction. In line with this suggestion, a recent study using a social interaction paradigm (Preller et al. 2014) demonstrated diminished emotional engagement and blunted reward responses in the medial orbitofrontal cortex of cocaine users that were related to real-life social network size. These results highlight the importance of social reward in the treatment of drug addiction and point to the potential of oxytocin-based therapeutics.

3.4   Schizophrenia

Reward processing in patients suffering from schizophrenia represents an area of particular clinical interest since motivational deficits often affect patients' quality of life and the common drug treatment is of limited effect. Not only motivational deficits can be seen as a result of anhedonia, but also a dissociation between the joyful reaction to a rewarding stimulus and the motivational behavior could be detected: Patients with schizophrenia show relatively intact consummatory pleasure, but a limited motivation to achieve a reward.

Irregularities in dopamine transmission are an important part of the pathophysiology of schizophrenia. Motivational deficits in patients suffering from schizophrenia may be related to orbitofrontal cortex-driven value representation deficits as well as to deficits in 'effort–cost' computation (Strauss et al. 2014). In the latter case, an overexpression of postsynaptic D2 receptors rather than reduced striatal dopamine release as well as cingulate dysfunction might contribute to aberrant effort–value computations in patients suffering from schizophrenia. Moreover, in previous studies, impairments in reward-related learning in people with schizophrenia were found, which were associated with disturbed ventral striatal activation: For example, individuals suffering from schizophrenia showed

reduced BOLD activation in the ventral striatum, including the nucleus accumbens, in response to prediction errors (Schlagenhauf et al. 2014). Furthermore, patients showed inappropriately strong ventral striatal activations in response to neutral stimuli as compared to healthy controls (e.g., Diaconescu et al. 2011). These findings suggest that alterations in the mesolimbic dopamine system underlie deficits in reward-based learning. As a result, the discrimination between important and unimportant environmental stimuli appears to be more difficult for patients suffering from schizophrenia. Consequently, 'aberrant salience' to nonrelevant stimuli may underlie some psychotic symptoms (Mier and Kirsch 2017), whereas decreased salience attribution to reward-predicting cues may be associated with negative symptoms like motivational deficits and avolition.

Several studies that examined monetary reward anticipation in schizophrenic patients are consistent with this interpretation. fMRI studies showed a significantly reduced activation in the ventral striatum in unmedicated and drug-naïve patients suffering from schizophrenia during the anticipation of monetary gains, indicating a dysfunction of the reward system in schizophrenic patients (e.g., Juckel et al. 2006a). In unmedicated patients, the ventral striatal hypoactivity is correlated with negative symptoms, while positive symptoms can be seen as a hyper-responsiveness of the reward system. Studies in treated patients showed a less pronounced hypofunction in the ventral striatum during reward anticipation when patients were treated with atypical, but not with typical antipsychotics—this can be explained by a stronger blockade of D2 receptors by typical antipsychotics (e.g., Juckel et al. 2006b).

So far, all studies on reward anticipation in schizophrenia have used monetary rewards. However, there is evidence that disturbed social reward processing may play a particular role in schizophrenia. Patients with schizophrenia have severe impairments in social functioning and show reduced engagement in social interactions—it seems plausible to assume that there is a disturbed sensitivity to social rewards. A recent fMRI study using a trust game supports this hypothesis: Gromann et al. (2013) found decreased striatal activity in patients with schizophrenia, which was interpreted as a diminished sensitivity to rewarding aspects of social interaction, resulting in reduced motivation to seek interaction. In addition, a behavioral trust game study (Fett et al. 2012) demonstrated that patients with psychosis not only showed lower initial levels of trust, but also were unable to change their trusting behavior according to the interaction partner's behavior—this might reflect a prediction problem and insensitivity to social reward.

4 Summary and Outlook

To conclude, there is evidence that the dopaminergic reward network is of crucial importance for social interaction. Mesocorticolimbic activity is suggested to represent a 'common currency' for the personal reward value of social and nonsocial rewards and to motivate social behavior. However, there is also evidence for

differences between social and nonsocial reward processing. For example, the neuropeptide oxytocin is suggested to be involved in the activation of the dopaminergic system in response to social stimuli. Although there is still no clear picture, several psychiatric disorders have been reported to be associated with disturbed social reward processing. Future research will need to clarify, which aspects of reward processing might be dysfunctional in these disorders and whether for example diminished personal reward values of social rewards can be increased by therapeutic interventions.

References

Beaver JD, Lawrence AD, van Ditzhuijzen J et al (2006) Individual differences in reward drive predict neural responses to images of food. J Neurosci 26:5160–5166. doi:10.1523/JNEUROSCI.0350-06.2006

Berridge KC, Robinson TE (1998) What is the role of dopamine in reward: hedonics, learning, or incentive salience? Brain Res Rev 28:308–367

Braams BR, Güroğlu B, De Water E et al (2014) Reward-related neural responses are dependent on the beneficiary. Soc Cogn Affect Neurosci 9:1030–1037. doi:10.1093/scan/nst077

Chevallier C, Kohls G, Troiani V et al (2012) The social motivation theory of autism. Trends Cogn Sci 16:231–238

Daniel R, Pollmann S (2014) A universal role of the ventral striatum in reward-based learning: evidence from human studies. Neurobiol Learn Mem 114:90–100. doi:10.1016/j.nlm.2014.05.002

Delmonte S, Balsters JH, McGrath J et al (2012) Social and monetary reward processing in autism spectrum disorders. Mol Autism 3:7. doi:10.1186/2040-2392-3-7

Diaconescu AO, Jensen J, Wang H et al (2011) Aberrant effective connectivity in schizophrenia patients during appetitive conditioning. Front Hum Neurosci 4:239. doi:10.3389/fnhum.2010.00239

Dichter G, Adolphs R (2012) Reward processing in autism: a thematic series. J Neurodev Disord 4:20. doi:10.1186/1866-1955-4-20

Eisenegger C, Pedroni A, Rieskamp J et al (2013) DAT1 polymorphism determines L-DOPA effects on learning about others' prosociality. PLoS ONE. doi:10.1371/journal.pone.0067820

Enter D, Colzato LS, Roelofs K (2012) Dopamine transporter polymorphisms affect social approach-avoidance tendencies. Genes, Brain Behav 11:671–676. doi:10.1111/j.1601-183X.2012.00791.x

Evans SL, Monte OD, Noble P, Averbeck BB (2013) Intranasal oxytocin effects on social cognition: a critique. Brain Res 1580:69–77. doi:10.1016/j.brainres.2013.11.008

Fareri DS, Niznikiewicz MA, Lee VK, Delgado MR (2012) Social network modulation of reward-related signals. J Neurosci 32:9045–9052. doi:10.1523/JNEUROSCI.0610-12.2012

Fett AKJ, Shergill SS, Joyce DW et al (2012) To trust or not to trust: the dynamics of social interaction in psychosis. Brain 135:976–984. doi:10.1093/brain/awr359

Gregory R, Cheng H, Rupp HA et al (2015) Oxytocin increases VTA activation to infant and sexual stimuli in nulliparous and postpartum women. Horm Behav 69:82–88. doi:10.1016/j.yhbeh.2014.12.009

Gromann PM, Heslenfeld DJ, Fett AK et al (2013) Trust versus paranoia: abnormal response to social reward in psychotic illness. Brain 136:1968–1975. doi:10.1093/brain/awt076

Groppe SE, Gossen A, Rademacher L et al (2013) Oxytocin influences processing of socially relevant cues in the ventral tegmental area of the human brain. Biol Psychiatry 74:172–179

Gross J, Woelbert E, Zimmermann J et al (2014) Value signals in the prefrontal cortex predict individual preferences across reward categories. J Neurosci 34:7580–7586. doi:10.1523/JNEUROSCI.5082-13.2014

Guastella A, Hickie I (2015) Oxytocin treatment, circuitry and autism: a critical review of the literature placing oxytocin into the autism context. Biol Psychiatry. doi:10.1016/j.biopsych.2015.06.028

Haber SN, Knutson B (2010) The reward circuit: linking primate anatomy and human imaging. Neuropsychopharmacology 35:4–26. doi:10.1038/npp.2009.129

Izuma K, Saito DN, Sadato N (2008) Processing of social and monetary rewards in the human striatum. Neuron 58:284–294. doi:10.1016/j.neuron.2008.03.020

Juckel G, Schlagenhauf F, Koslowski M et al (2006a) Dysfunction of ventral striatal reward prediction in schizophrenia. Neuroimage 29:409–416. doi:10.1016/j.neuroimage.2005.07.051

Juckel G, Schlagenhauf F, Koslowski M et al (2006b) Dysfunction of ventral striatal reward prediction in schizophrenic patients treated with typical, not atypical, neuroleptics. Psychopharmacology 187:222–228. doi:10.1007/s00213-006-0405-4

Kirsch P, Schienle A, Stark R et al (2003) Anticipation of reward in a nonaversive differential conditioning paradigm and the brain reward system: an event-related fMRI study. Neuroimage 20:1086–1095. doi:10.1016/S1053-8119(03)00381-1

Klucharev V, Hytönen K, Rijpkema M et al (2009) Reinforcement learning signal predicts social conformity. Neuron 61:140–151. doi:10.1016/j.neuron.2008.11.027

Knutson B, Adams CM, Fong GW, Hommer D (2001) Anticipation of increasing monetary reward selectively recruits nucleus accumbens. J Neurosci 21:RC159

Knutson B, Gibbs SEB (2007) Linking nucleus accumbens dopamine and blood oxygenation. Psychopharmacology 191:813–822. doi:10.1007/s00213-006-0686-7

Kohls G, Schulte-Rüther M, Nehrkorn B et al (2013) Reward system dysfunction in autism spectrum disorders. Soc Cogn Affect Neurosci 8:565–572. doi:10.1093/scan/nss033

Kohls G, Thönessen H, Bartley GK et al (2014) Differentiating neural reward responsiveness in autism versus ADHD. Dev Cogn Neurosci 10:104–116. doi:10.1016/j.dcn.2014.08.003

Krach S, Paulus FM, Bodden M, Kircher T (2010) The rewarding nature of social interactions. Front Behav Neurosci 4:22. doi:10.3389/fnbeh.2010.00022

Lega B, Kahana M, Jaggi J (2011) Neuronal and oscillatory activity during reward processing in the human ventral striatum 22:795–800. doi:10.1097/WNR.0b013e32834b2975.Neuronal

Liu X, Hairston J, Schrier M, Fan J (2011) NIH Public Access 35:1219–1236. doi:10.1016/j.neubiorev.2010.12.012.Common

Luman M, Tripp G, Scheres A (2010) Identifying the neurobiology of altered reinforcement sensitivity in ADHD: a review and research agenda. Neurosci Biobehav Rev 34:744–754

McGregor IS, Bowen MT (2012) Breaking the loop: oxytocin as a potential treatment for drug addiction. Horm Behav 61:331–339. doi:10.1016/j.yhbeh.2011.12.001

Mier D, Kirsch P (2017) Social-cognitive deficits in schizophrenia. Curr Top Behav Neurosci 30:397–409

Mirenowicz J, Schultz W (1996) Preferential activation of midbrain dopamine neurons by appetitive rather that aversive stimuli. Nature 379:449–451

Moll J, Krueger F, Zahn R et al (2006) Human fronto-mesolimbic networks guide decisions about charitable donation. Proc Natl Acad Sci USA 103:15623–15628. doi:10.1073/pnas.0604475103

Morelli SA, Torre JB, Eisenberger NI (2014) The neural bases of feeling understood and not understood. Soc Cogn Affect Neurosci 1–7. doi:10.1093/scan/nst191

Müller-Pinzler L, Krach S, Krämer UM, Paulus FM (2017) The social neuroscience of interpersonal emotions. Curr Top Behav Neurosci 30:241–256

Paulus FM, Rademacher L, Schäfer TAJ, Müller-Pinzler L, Krach S (2015) Journal impact factor shapes scientists' reward signal in the prospect of publication. PLoS One 10(11):e0142537. doi:10.1371/journal.pone.0142537

Peters J, Bromberg U, Schneider S et al (2011) Lower ventral striatal activation during reward anticipation in adolescent smokers. Am J Psychiatry 168:540–549. doi:10.1176/appi.ajp.2010.10071024

Poustka L, Kamp-Becker I (2017) Current practice and future avenues in autism therapy. Curr Top Behav Neurosci 30:357–378

Preller KH, Herdener M, Schilbach L et al (2014) Functional changes of the reward system underlie blunted response to social gaze in cocaine users. Proc Natl Acad Sci USA 111:2842–2847. doi:10.1073/pnas.1317090111

Rademacher L, Krach S, Kohls G et al (2010) Dissociation of neural networks for anticipation and consumption of monetary and social rewards. Neuroimage 49:3276–3285. doi:10.1016/j.neuroimage.2009.10.089

Rekers Y, Haun DBM, Tomasello M (2011) Children, but not chimpanzees, prefer to collaborate. Curr Biol 21:1756–1758. doi:10.1016/j.cub.2011.08.066

Rilling J, Gutman D, Zeh T et al (2002) A neural basis for social cooperation. Neuron 35:395–405. doi:10.1016/S0896-6273(02)00755-9 [pii]

Robinson TE, Berridge KC (2000) The psychology and neurobiology of addiction: an incentive-sensitization view. Addiction 95(Suppl 2):S91–S117. doi:10.1080/09652140050111681

Sauer C, Montag C, Reuter M, Kirsch P (2013) Imaging oxytocin? dopamine interactions: an epistasis effect of CD38 and COMT gene variants influences the impact of oxytocin on amygdala activation to social stimuli. Front Neurosci 7:1–9. doi:10.3389/fnins.2013.00045

Scheele D, Wille A, Kendrick KM et al (2013) Oxytocin enhances brain reward system responses in men viewing the face of their female partner. Proc Natl Acad Sci USA 110:20308–20313. doi:10.1073/pnas.1314190110

Scheres A, Milham MP, Knutson B, Castellanos FX (2007) Ventral striatal hypo responsiveness during reward anticipation in attention-deficit/hyperactivity disorder. Biol Psychiatry 61:720–724. doi:10.1016/j.biopsych.2006.04.042

Schlagenhauf F, Huys QJM, Deserno L et al (2014) Striatal dysfunction during reversal learning in unmedicated schizophrenia patients. Neuroimage 89:171–180. doi:10.1016/j.neuroimage.2013.11.034

Schultz W (2013) Updating dopamine reward signals. Curr Opin Neurobiol 23:229–238. doi:10.1016/j.conb.2012.11.012

Scott-Van Zeeland AA, Dapretto M, Ghahremani DG et al (2010) Reward processing in autism. Autism Res 3:53–67. doi:10.1002/aur.122

Sescousse G, Li Y, Dreher J-C (2014) A common currency for the computation of motivational values in the human striatum. Soc Cogn Affect Neurosci 1–7. doi:10.1093/scan/nsu074

Skuse DH, Gallagher L (2009) Dopaminergic-neuropeptide interactions in the social brain. Trends Cogn Sci 13:27–35. doi:10.1016/j.tics.2008.09.007

Solomon M, Frank M, Ragland J et al (2015) Feedback-driven trial-by-trial learning in autism spectrum disorders. Am J Psychiatry 172:173–181

Spreckelmeyer KN, Krach S, Kohls G et al (2009) Anticipation of monetary and social reward differently activates mesolimbic brain structures in men and women. Soc Cogn Affect Neurosci 4:158–165. doi:10.1093/scan/nsn051

Stark R, Schienle A, Girod C et al (2005) Erotic and disgust-inducing pictures—differences in the hemodynamic responses of the brain. Biol Psychol 70:19–29. doi:10.1016/j.biopsycho.2004.11.014

Strang S, Park SQ (2017) Human cooperation and its underlying mechanisms. Curr Top Behav Neurosci 30:223–239

Strathearn L (2011) Maternal neglect: oxytocin, dopamine and the neurobiology of attachment. J Neuroendocrinol 23:1054–1065

Strauss GP, Waltz JA, Gold JM (2014) A review of reward processing and motivational impairment in schizophrenia. Schizophr Bull 40:107–116. doi:10.1093/schbul/sbt197

Tripp G, Wickens JR (2008) Research review: dopamine transfer deficit: a neurobiological theory of altered reinforcement mechanisms in ADHD. J Child Psychol Psychiatry Allied Discip 49:691–704

Von Rhein D, Cools R, Zwiers MP et al (2015) Increased neural responses to reward in adolescents and young adults with attention-deficit/hyperactivity disorder and their unaffected siblings. J Am Acad Child Adolesc Psychiatry 54:394–402. doi:10.1016/j.jaac.2015.02.012

Wrase J, Schlagenhauf F, Kienast T et al (2007) Dysfunction of reward processing correlates with alcohol craving in detoxified alcoholics. Neuroimage 35:787–794. doi:10.1016/j.neuroimage.2006.11.043

Zaghloul KA, Blanco JA, Weidemann CT et al (2009) Human substantia nigra neurons encode unexpected financial rewards. Science 323:1496–1499. doi:10.1126/science.1167342