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Dopamine and Addiction

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Abstract

Addiction is commonly identified with habitual nonmedical self-administration of drugs. It is usually defined by characteristics of intoxication or by characteristics of withdrawal symptoms. Such addictions can also be defined in terms of the brain mechanisms they activate; most addictive drugs cause elevations in extracellular levels of the neurotransmitter dopamine. Animals unable to synthesize or use dopamine lack the conditioned reflexes discussed by Pavlov or the appetitive behavior discussed by Craig; they have only unconditioned consummatory reflexes. Burst discharges (phasic firing) of dopamine-containing neurons are necessary to establish long-term memories associating predictive stimuli with rewards and punishers. Independent discharges of dopamine neurons (tonic or pacemaker firing) determine the motivation to respond to such cues. As a result of habitual intake of addictive drugs, dopamine receptors expressed in the brain are decreased, thereby reducing interest in activities not already stamped in by habitual rewards.

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INTRODUCTION

Addiction refers to the compulsive nonmedical self-administration of drugs. Often used pejoratively, the term refers to drug taking done by other people or to drug taking despite negative side effects. The latter notion has been inferred from a statement by Alan Leshner (1997, p. 46), head of the National Institute on Drug Abuse, describing addiction as "compulsive drug seeking and use even in the face of negative health and social consequences." Negative consequences have been added to the discussion of addiction, as modeled by animals pressing a lever for a cocaine reward accompanied by either footshock (Deroche-Gamonet et al. 2004) or a tone previously associated with footshock (Vanderschuren & Everitt 2004). However, the idea of negative consequences is a human issue, and for humans, negative consequences are rarely experienced at the time of drug taking. Rather, they are the imagined future consequences, read about or heard about, such as possible or probable cancer, heart problems, or incarceration. This notion of addiction has narrowed the discussion to drug addiction and links the phenomenon to drugs like heroin and alcohol that, when withdrawn, have prominent aversive withdrawal symptoms.

One problem with these definitions is that they do not apply equally across the range of addictive drugs and they do not apply equally to other powerful rewards. Thus, arguments develop around issues such as whether marijuana, gambling, or high-calorie food is addictive.

Although the direct effects and withdrawal symptoms vary across addictive drugs, all such drugs and some other rewards impact the brain reward system and the extracellular fluctuations of the implicated neurotransmitter dopamine. In this review, we first discuss the role of dopamine in physiology and behavior and then describe how addictive drugs and substances activate the dopamine system to perpetuate maladaptive behavior.

THE DOPAMINE SYSTEM AND BEHAVIOR

Dopamine is a neurotransmitter: a chemical synthesized by neurons and released in ways that influence the activity of other neurons. It is sometimes identified as a neuromodulator—a subtype of neurotransmitter—because it acts more to modulate the sensitivity to other neurotransmitters rather than substituting for them. In the striatum, where it has its most obvious, but not only, motivational functions, dopamine modulates the excitatory control of glutamate-releasing input neurons on GABA-releasing output neurons. Dopamine facilitates the development of long-lasting cellular modifications that either potentiate or depress the influence of glutamate, and these adaptations determine the effectiveness of reward predictors to control subsequent search behaviors. Discussed in the following sections, four aspects of dopamine function are related to addiction: (*a*) Animals lacking dopamine have only unconditioned reflexes, (*b*) phasic firing of dopamine neurons stamps in (reinforces) learning, (*c*) tonic firing of dopamine neurons controls or contributes to motivation, and (*d*) habit reliance decreases interest in other incentives.

Dopamine-Depleted Animals Have Only Unconditioned Reflexes

Adult animals with selective damage to their dopamine system are akinetic. If not artificially fed, they die of starvation (Anand & Brobeck 1951, Stricker & Zigmond 1976, Ungerstedt 1971). They have adequate motor capacity: They respond to footshock (Cooper et al. 1973, Laverty & Taylor 1970); retain the ability to shake their heads, groom, and attempt to escape from restraint; if placed in deep water, they swim; and if placed in an ice bath, they escape (Keefe et al. 1989). However, dopamine-depleted animals do not show spontaneous movements in an open field (Ungerstedt 1971); are only minimally responsive to mild touch, auditory, or visual stimuli; and fail to follow moving stimuli or respond to food odors (Marshall & Teitelbaum 1974, Marshall et al. 1971). These animals reject water or food offered in standard tests, allowing it to dribble onto the floors of their cages (Anand & Brobeck 1951, Stricker & Zigmond 1976, Ungerstedt 1971). Simply put, these animals have unconditioned reflexes and habits learned prior to being lesioned, but they cannot learn new responses. Moreover, after being lesioned, they lack motivation to react to predictive stimuli. This is critical for life; predictive stimuli guide the animal from one reward to another (Bindra 1969, Bolles 1972).

Cell biologists can alter the ability of animals to synthesize tyrosine hydroxylase—a dopamine precursor—from nutrients. Such animals die in utero because of heart failure. However, if the ability to synthesize the by-products of dopamine—two related neurotransmitters norepinephrine and epinephrine—is restored, then the animals are born normally and survive for a few weeks. They lose weight, are hypoactive, groom only minimally, and have hunched posture (Zhou & Palmiter 1995). Like normal animals depleted of dopamine, they fail to search for and bite at food; if not treated, they also die of starvation (Palmiter 2008). In this case, the animals never learned to respond to predictive stimuli; they also have only unconditioned (Pavlov 1927) consummatory (Craig 1918) reflexes.

The impairments in tyrosine-deficient mice can be reversed by infusions of the dopamine-precursor L-DOPA (Denenberg et al. 2004, Heusner et al. 2003, Zhou & Palmiter 1995). This precursor is taken up and metabolized to dopamine, which is stored by the traditional neurons and becomes released when these neurons are active. Twice-daily L-DOPA injections are sufficient to maintain nearly normal body weight in these animals (Zhou & Palmiter 1995); once-daily L-DOPA injections restore feeding for approximately 8 hours, but this is not sufficient for survival (Szczypka et al. 1999). Injections of direct dopamine agonists—drugs that act at dopamine receptors—independent of whether the dopamine system is active—are not effective; indeed, they have the opposite effect. It is necessary to have dopamine released only at times when the cells are

activated (Sotak et al. 2005). Local delivery of genes for synthesis of tyrosine hydroxylase (and of a required cofactor) can restore dopamine function in localized regions. Dorsal striatal injections restore the ability to eat and drink (Szczypka et al. 2001), search for pups (Henschen et al. 2013) and perform maternal behavior (Henschen et al. 2013), whereas ventral striatal injections restore normal locomotion, a component of finding distant rewards (Heusner et al. 2003).

In summary, dopamine depletion leaves animals unable to learn conditioned reflexes. Animals born without dopamine never develop conditioned reflexes, and animals that lose their dopamine systems as adults have the memory traces for conditioned reflexes but no longer show these responses to predictive stimuli. The ability of the system to condition burst responding to reward predictors allows an animal to learn to find food, shelter, and social contacts and help it to avoid painful or threatening stimuli.

Phasic Dopamine Responses: Burst Firing and Instrumental Learning

Search habits depend on the learning of associations between unconditioned rewarding stimuli and the stimuli that immediately preceded (predicted) them. In addition, two sources of neuronal plasticity are involved: One occurs between excitatory terminals and the dopamine neurons (Saal et al. 2003), and the other occurs between the striatal glutamatergic excitatory inputs and GABAergic output neurons that receive modulating synaptic input from the dopamine system. Although studies of dopamine projections to the striatum have dominated the literature, the dopamine system projects to other parts of the brain, and lesion and pharmacological studies suggest that they play similar, but not identical, roles in drug seeking and drug withdrawal (McGregor et al. 1994, 1996).

The dopaminergic response to rewarding stimuli is phasic activation (burst firing). Dopamine neurons have an unconditioned response to intense stimuli (Horvitz 2000), novel stimuli (Ljungberg et al. 1992, Steinfels et al. 1983), rewards, and punishers (Chiodo et al. 1979, Schultz 1986, Strecker & Jacobs 1985); its response is termed phasic activation, better known as burst firing. The responses to punishers are complex, but the responses to rewards such as food are reflexive, linked, bursts of discharges (Schultz 1986). Similar responses develop in response to predictors of food as a result of contiguity; through repeated associations between predictors and food, dopamine neurons come to respond with bursts to stimuli that immediately precede and reliably predict the reward (Ljungberg et al. 1992). As immediate predictors are learned, burst responses develop to increasingly earlier predictors (Schultz et al. 1993). As discussed below, predictors of addictive drugs also develop burst responses in the dopamine system.

Burst firing involves groups of two to approximately eight discharges (occasionally longer) in response to excitatory inputs (Grace & Bunney 1984b). Bursts can be separated from spontaneous firing by the intervals and intensities of successive action potentials; there are decreasing amplitudes of successive discharges, and the intervals between the first and second potentials (~60 ms) and between subsequent intervals (~120 ms) are short (Grace & Bunney 1984b). In contrast, single-spike discharges are longer and more variable, with mean intervals between 150 and 500 ms (Grace & Bunney 1984b). Burst firing is triggered by glutamatergic or cholinergic inputs to the dopamine system (Grace & Bunney 1984a); these inputs arise from two related sensory nuclei in the brainstem, the laterodorsal and pontine tegmental nuclei (Floresco et al. 2003, Lodge & Grace 2006).

The responses to punishing stimuli are also important in studies of addiction, but they remain to be fully understood. Not all dopaminergic neurons burst in response to punishers; some dopamine neurons are inhibited by punishers and punishment-predictors (McCutcheon et al.

2012). Further research is needed in this area because recent evidence suggests that, in rats, predictors that cocaine will be delayed, not available at the time an animal is ready to work for it, become aversive. Aversive stimuli establish an aversive state of mind, a state the addicted animal avoids by taking more cocaine (Wheeler et al. 2015). It seems likely that a similar pattern of acquired motivation will be found for other addictive drugs.

Phasic release of dopamine is detected by fast-scan cyclic voltammetry. There has been longstanding debate about the methods used to measure extracellular dopamine. Microdialysis detects concentrations of dopamine well below 1.0 nM (Westerink et al. 1987a) but may underestimate dopamine levels by chronically depleting the local analyte and by disturbing and altering the tissue around the large dialysis probe (Benveniste 1989, Nesbitt et al. 2013). Voltammetry has a detection threshold of approximately 20 nM (Owesson-White et al. 2012), too high to measure baseline firing (as suggested by no-net-flux microdialysis; see below) (Parsons & Justice 1992, Sam & Justice 1996). Thus, voltammetry detects some, but does not provide an indication of all, phasic discharges from the local dopamine terminals.

Voltammetry has been progressively refined over the past two decades, such that one version—fast-scan cyclic voltammetry (FSCV)—identifies only bursting release of dopamine accumulations, reaching well above 20-nM concentrations (Fox & Wightman 2017, Owesson-White et al. 2012). Burst firing saturates the dopamine uptake mechanism and causes accumulations of dopamine that penetrate into this range (Gonon 1988). However, the concentrations from bursts are localized. Concentration decreases rapidly from the site of dopamine release, diffusing to baseline levels as it spreads a few micrometers from the release site (Cragg & Rice 2004, Rice & Cragg 2008). The FSCV method uses small probes that allow them—after required adjustments of probe placement (Phillips et al. 2003, Robinson et al. 2001)—to be near enough to release sites for such detection. A subsecond sampling method is used (10-ms samples every 100 ms) (Robinson et al. 2001), enabling FSCV to detect the accumulating local levels from repeated firing in bursts (Gonon 1988). Finally, background subtraction—the removal of the momentary value measured immediately prior to the observed peaks—eliminates the contribution of the baseline dopamine signal (Heien et al. 2004). By background-subtracting baseline dopamine levels, current FSCV eliminates any indication of the baseline dopamine levels contributed by single impulses.

Thus, the most reasonable interpretation is that FSCV identifies the fast, local, and cue-induced fluctuations of variably placed synapses in the striatum, whereas microdialysis measures primarily the slow, distributed, and temporally averaged changes due to fluctuations associated with the motivational state of the animal (discussed in the section titled Tonic Activation Is Measured by Microdialysis). FSCV removes from its estimates any contributions of tonic firing, reflecting only a portion of accumulated concentrations due to local phasic firing and detecting burst release that is important for stamping in temporally and spatially distributed memory traces. Microdialysis is relatively insensitive to phasic firing because it averages firing that is spatially and temporally distributed, such that individual and peak concentrations are largely lost by uptake and diffusion into background concentrations.

The dopamine system is heterogeneous. Both the dopamine system and the synaptic targets of the dopamine system are heterogeneous. The dopamine system projects to the striatum, medial prefrontal cortex, hippocampus, amygdala, and other areas (Menegas et al. 2018, Ogawa & Watabe-Uchida 2017), each of which serves different functions. Some dopamine neurons respond to unconditioned rewards (Ljungberg et al. 1992); others respond to unconditioned punishment (Brischoux et al. 2009, Lammel et al. 2011). Some respond to otherwise neutral stimuli that have come to predict reward (Ljungberg et al. 1992); others respond to otherwise neutral stimuli that

have come to predict punishment (Mileykovskiy & Morales 2011). Even within the reward category, a predictor of feeding may modulate moving to where the food will appear while another modulates approaching a possible social partner. Thus, there is heterogeneity in the responses of dopaminergic neurons themselves.

Within the striatum, close to half of the output neurons express only D_1 receptors, and the other half express only D_2 receptors (only a few cells express both) (Gerfen & Surmeier 2011). D_1 receptors have low affinity for dopamine (Rice & Cragg 2008, Richfield et al. 1989) and are thus infrequently occupied by dopamine molecules. When D_1-expressing output neurons are activated, they encourage action (Kravitz et al. 2012). D_2 receptors have high affinity for dopamine (Rice & Cragg 2008, Richfield et al. 1989) and are usually occupied by dopamine molecules (Dreyer et al. 2010). When D_2-expressing medium spiny neurons are further activated, they are generally thought to inhibit action (Kravitz et al. 2012). D_1- and D_2-expressing output neurons have distinct projection targets, although there is some overlap from the ventral striatal output neurons (Kupchik et al. 2015). The distinction between D_1 and D_2 activations was once thought to mediate periods of activity and alternating periods of inactivity, but we now know that in the dorsal striatum D_1 and D_2 striatal neurons are usually activated at or nearly at the same times (Cui et al. 2013, Tecuapetla et al. 2016). Therefore, dopamine's activation of D_1 striatal neurons appears to enable one set of movements while its activation of D_2 striatal neurons disables multiple sets of potentially conflicting movements.

Phasic activation of dopaminergic neurons modifies synaptic transmission. Phasic activation of the dopamine system by unconditioned rewards is essential for establishing the link between potentially predictive environmental stimuli and the unconditioned rewards that follow them (Ljungberg et al. 1992, Schultz 1997); these connections result from synaptic changes in the brain. In the striatum, medium spiny neurons show long-term potentiation (an increase in sensitivity to presynaptic input) or long-term depression (a reduction in sensitivity to presynaptic input) of synaptic transmission, and dopamine receptor activation is critically involved in these synaptic modifications (Creed et al. 2016, Gerfen & Surmeier 2011). Electrical self-stimulation of the dopamine system, causing burst firing, results in long-term potentiation of forebrain synapses, and this plasticity involves D_1 receptor activation (Reynolds et al. 2001, Wickens et al. 2003); the medium spiny neuron must receive glutamatergic and dopaminergic input within the same 0.3–2.0-s time window for the potentiation of the glutamate connection to GABAergic output neurons (Yagishita et al. 2014). These plastic changes are important for learning a stimulus chain to find rewards, and they can be driven by the rewarding effects of drugs of abuse (Creed et al. 2016, Zhu et al. 2016). The same input promotes long-term depression of excitatory signaling in D_2-expressing striatal neurons, which is important for suppressing competing response options to those driven by potentiated inputs to D_1-expressing striatal neurons.

Learning of this type is distributed across structures; dopamine enhancement in the dorsal striatum is involved in learning to repeat responses that have just been rewarded, but other structures learn other associations (McDonald & White 1993). However, even within the striatum, there is further differentiation of function, as adjacent neurons can participate in distinct tasks (Carelli & Deadwyler 1994, Roop et al. 2002). In the striatum, coincident activation of dopamine D_1 receptors and NMDA (*N*-methyl-D-aspartate) receptors is required for long-term facilitation (Beutler et al. 2011, Smith-Roe & Kelley 2000). Dopamine neurons also undergo long-term potentiation (Saal et al. 2003); however, in this case, NMDA receptors are not involved (Parker et al. 2010).

Recent optogenetic studies have confirmed a causal link between phasic activation of the dopamine system and reward learning. Animals learn to lever press resulting in optogenetic

activation of dopamine neurons, which is sufficient to condition nose-poking or lever-pressing habits (Ilango et al. 2014, Witten et al. 2011). Animals will also respond to optogenetic stimulation limited to dopaminergic terminals in the nucleus accumbens, depending on both D_1 and D_2 receptor activation (Steinberg et al. 2014). As predictors of reward become associated with rewards, they elicit burst firing of dopamine neurons; the resultant phasic dopamine release in the striatum causes long-term linkage of connections between recently active glutamate inputs and GABAergic output neurons. These synaptic adaptations are the neural basis of associative memory between reward-predicting cues and subsequent rewards; they are the mechanism by which these cues come to guide sequences of reward seeking.

Low Dopamine Levels Are Aversive

Reduced activity in a large subset of dopaminergic projections to the ventral striatum is associated with aversion. Optogenetic inhibition of ventral tegmental area dopamine neurons produces avoidance of associated places and cues, an effect that depends on D_2 receptor signaling (Danjo et al. 2014, Ilango et al. 2014). Inhibition of these neurons via D_2 receptor activation causes a conditioned place aversion and mediates negative affect (Liu et al. 2008). Aversive stimuli of various sensory modalities broadly inhibit dopamine release in the ventral striatum (de Jong et al. 2018, Menegas et al. 2018). These studies are consistent with reports that aversive stimuli preferentially activate a subset of D_2-expressing striatal output neurons (Xiu et al. 2014), and they provide causal evidence that reductions in striatal dopamine are aversive.

Rat vocalizations confirm that drug self-administration is pleasant. During cocaine self-administration or when morphine is given, rats increase high-frequency (~50-kHz) vocalizations that are associated with pleasurable stimuli; low-frequency (22-kHz) vocalizations dominate when aversive stimuli or opiate antagonists are given (Haney & Miczek 1994, Scardochio et al. 2015). During cocaine testing, when experimenter-administered doses are programmed at lower doses or lower frequency than what animals would normally self-select, 22-kHz vocalizations are prevalent; when higher than normal cocaine doses are given, 50-kHz vocalizations appear and 22-kHz vocalizations decrease (Barker et al. 2010, 2014).

When a rat is repeatedly exposed to a flavored saccharin solution that is not followed immediately by cocaine but that precedes a distant cocaine self-administration session, the taste of this normally rewarding saccharin solution reduces phasic dopamine release in the ventral striatum, becomes aversive, and alters striatal neural activity in a manner similar to the effects of quinine (Wheeler et al. 2008, 2011, 2015). The saccharin becomes aversive, as demonstrated in a taste-reactivity test where infusing the solution into the animal's mouth induces gaping and ejection of the solution, the same responses seen when quinine is injected. By contrast, if the saccharin solution predicts immediate drug delivery or delayed access to saline self-administration, it elicits licking and swallowing, the normal responses to sweet substances. The strength of the learned aversion to saccharin that predicts delayed cocaine self-administration is correlated with early-session drug taking; rats that show more aversive responses to the conditioned taste subsequently self-administer more cocaine (Wheeler et al. 2008). A similar correlation between degree of aversion and amount of subsequent drug taking has been shown with other addictive drugs (Wise et al. 1976). After the drug-seeking response has been largely extinguished (during several cocaine-free extinction sessions), presentation of the delayed cocaine predictive taste cue reinstates the seeking behavior, doubling responses to the partially extinguished cues for immediate drug delivery. Presentation of unconditioned saccharin in control animals does not increase responding (Wheeler et al. 2015).

Presentation of unconditioned quinine—which also reduces dopamine and creates an aversive state—similarly reinstates (or sets the stage for reinstatement) of cocaine seeking. Release of the stress hormone corticotropin-releasing factor (CRF) (Zorrilla et al. 2014) is one source of dopamine inhibition. Microinjections of a CRF receptor antagonist into the region of dopamine cell bodies attenuates part of the dopaminergic inhibition and blocks drug seeking (Twining et al. 2015).

In humans, cocaine-predictive cues are clearly aversive when presented in the absence of the drug. They increase self-reported indexes of anger, confusion, tension, and depression (Robbins et al. 2000). They cause anxiety, engage physiological stress systems, and induce a reportedly negative affective craving state (Blaine et al. 2018). The physiological impact of drug-predictive cues is often similar to that evoked in humans by stressful stimuli or imagery (Sinha 2008). Thus, one of the suggested motivators of drug seeking in addicts is a desire to alleviate a cue-induced negative affective state.

Animals learn to avoid cues that predict the unavailability of addictive drugs, yet the brain mechanisms by which this happens are not well understood. In the course of developing drug-seeking habits, many aspects of brain function are adjusted (Lüscher & Malenka 2011, Nestler 2013). What remains to be clarified is which of these central events cause drug taking and which are only consequences (Wise & Koob 2014).

Tonic Dopamine Release Determines Motivational Arousal

Pacemaker firing of the dopamine system—repeated independent discharges—is also important and plays a role in motivational arousal. Motivational arousal reflects the willingness to exert effort for a reward (Correa et al. 2002, Salamone et al. 2007, Wise 1987). Pacemaker firing refers to a series of individual discharges, triggered by a slow depolarizing current within the dopaminergic neurons (Grace 1991). The neurons discharge somewhat irregularly (discharge rate is also influenced by variations in GABA-mediated inhibition) at 3–8-Hz frequency with interspike intervals approximately three times longer than those seen in burst firing (Grace & Bunney 1984b). Dopamine is released from multiple sites along the length of dopamine axons (Liu et al. 2018), few of which show synaptic contacts (Yung et al. 1996). It diffuses from release sites to act largely by volume transmission (Agnati et al. 2010) at distant receptors. Unlike phasic dopamine peaks, it is measured at approximately the same level throughout the striatum. Because dopamine cannot invade areas of equal or higher concentration, it must be inactivated by reuptake or metabolism rather than by diffusion.

Tonic activation is measured by microdialysis. Dopamine levels maintained by pacemaker (single-impulse) firing are below the detection threshold for FSCV (detection threshold is ~20 nM) (Owesson-White et al. 2012). They can be detected by microdialysis, which has the sensitivity to detect dopamine levels as low as 0.1 nM (Westerink et al. 1987b). Pacemaker firing maintains dopamine levels in the range of ~2–10 nM. Whereas microdialysis does not differentiate the contributions from pacemaker firing and burst firing, the effects of burst firing have limited effects on microdialysis measurements because they are relatively infrequent and are distributed along the large surface of the microdialysis probe.

Tonic firing is normally modulated by hormones and peptides. In the normal environment, many factors—but not environmental stimuli (Schultz 1997)—can regulate the pacemaker firing of the dopamine system (Hsu et al. 2018). The system is controlled, for example, by stress (Wang et al. 2005) as well as feeding-related hormones (You et al. 2018) that act on dopaminergic neurons

or their inputs including leptin (Figlewicz et al. 2003, Fulton et al. 2006, Leinninger et al. 2009), insulin (Figlewicz et al. 2003), GLP-1 (Alhadeff et al. 2012), and ghrelin (Jerlhag et al. 2011). Hormones and peptides contribute to the control of the dopamine system by slow actions on dopamine neuron receptors altering the rate of pacemaker firing or by actions through GABA neurons (the inhibitory controllers of the dopamine system), which also influence the rate of tonic firing but do not cause burst firing.

Tonic firing determines motivational arousal. The contributions of dopamine released by pacemaker firing can be estimated in animals at rest under minimal stimulus conditions (Campbell & Sheffield 1953). Measured using two methods—no-net-flux and extrapolation to zero flow—baseline dopamine release in sated freely moving animals is ~4.2 nM in the ventral stratum (Parsons & Justice 1992). Blocking phasic dopaminergic activation by blocking either dopamine synthesis or packaging of dopamine into releasable vesicles establishes animals with no noticeable motivational arousal (Szczypka et al. 1999, Zhou & Palmiter 1995). By contrast, replacing dopamine or giving an immediate dopamine precursor restores it (Heusner et al. 2003, Szczypka et al. 2001, Zhou & Palmiter 1995). Depletion of dopamine by neurochemical lesions has the same effect as dopamine depletion (Ungerstedt 1971). The use of dopamine antagonists to reduce dopamine in trained animals produces the clearest evidence of decreased motivational arousal. These animals expend less energy in partial or progressive ratio schedules, reducing the effort they are willing to expend for a given reward (Salamone et al. 2007). In patients with Parkinson's disease, where dopamine levels are significantly decreased, both speed of hand movements in a placement task (Mazzoni et al. 2007) and willingness to squeeze a dynamometer decreased (Chong et al. 2015); when the patients were back on medication, squeezing increased (Chong et al. 2015). Together, these studies suggest that pacemaker dopamine release determines motivation rather than the ability to work for reward.

Conversely, elevating dopamine levels above baseline increases motivational arousal. Low doses of amphetamine have this effect (Wyvell & Berridge 2000), as does sensitizing the system by prior amphetamine experience (Wyvell & Berridge 2001). In a study with an inducible dopamine transporter knockdown that increased pacemaker firing but failed to alter burst firing, animals showed increased lever pressing for food in a progressive ratio task and increased choice for a more palatable food in a choice paradigm (Cagniard et al. 2006). A dopamine uptake inhibitor that doubled baseline dopamine levels increased willingness to ignore normal pellets and to work for high-carbohydrate pellets (Yohn et al. 2016). A low dose of amphetamine caused humans to increase effort for monetary rewards (Wardle et al. 2011).

In each case, decreased baseline dopamine levels are associated with decreased willingness to exert effort, and stimulation of the dopamine system reverses this effect. Although dopamine depletion attenuates responsiveness to predictive cues, it does not attenuate responsiveness to food (Ikemoto & Panksepp 1996). Dopamine is important for the motivation of seeking responses, but is not important for the unconditioned responses to the food or punisher. Dopamine levels represent a constantly updating signal about the value of a given situation, influencing the willingness to work to obtain reward (Hamid et al. 2016).

Dopamine Receptors Are Downregulated by Habitual Reward Seeking

Surface expression of D_2 dopamine receptors is decreased by long-term self-administration of addictive drugs such as opiates (Wang et al. 1997), cocaine (Nader et al. 2006, Volkow et al. 1993), methamphetamine (Volkow et al. 2001), alcohol (Volkow et al. 2007), and nicotine (Wiers et al. 2017). This effect also results from compulsive overeating (Johnson & Kenny 2010,

Volkow et al. 2008). D_2 receptors have high affinity for dopamine, and resting dopamine levels in the striatum keep these receptors frequently occupied. D_1 receptors have low affinity for dopamine and are activated primarily by high concentrations (burst firing) of dopaminergic neurons. Thus, it is not surprising that dramatic changes in D_2 receptor expression result from habitual activation. Conflicting evidence suggests that D_1 receptors are also decreased by habitual addictive drug use (Thanos et al. 2017).

Leaving potentiated habits strong, long-term decreases in dopamine receptor expression result in decreased sensitivity to the range of rewarding stimuli that are not already potentiated as part of established habits. Because such decreases are seen in obese individuals, a common mechanism may link overconsumption of energy-rich foods with addiction. The selective decrease in dopaminergic responsiveness to nonhabitual stimuli—measured by decreased expression of dopamine receptors—offers an interesting measure of addiction that extends dopamine beyond simple addiction to drugs.

ADDICTIVE DRUGS

Addictive Drugs Are Habit-Forming and Activate the Dopamine System

Burst firing by predictive stimuli that lead animals to addictive drugs must be learned; it develops when stimuli reliably precede the burst firing triggered by unconditioned rewards. Hebb (1949) outlined a mechanism for the development of burst firing to predictors. This burst firing of dopaminergic neurons in response to unconditioned rewards establishes burst-firing responses to predictive stimuli that immediately precede unconditioned rewards as well as long-term potentiation of synapses between glutamate-containing sensory neurons and D_1 striatal output neurons. It also establishes long-term depression of synapses between glutamate-containing sensory neurons and D_2 striatal output neurons. Long-term potentiation and long-term depression (which also develops in other regions receiving dopamine input) establish relatively permanent response habits by which sequences of environmental stimuli lead the animal to the drug.

We also know, though in much less detail, that depression of the dopamine system becomes established for cues that predict delayed rewards. In the case of cocaine, cues predicting delayed access to cocaine become aversive (see above). Addicts work to avoid cues that predict these delays, and avoidance becomes increasingly established as the drug habit becomes progressively learned. Although the effects of drugs that predict future but not immediate cues have not been tested with other addictive drugs, it seems likely that the effects of cocaine will prove true for other drugs.

Here we consider whether and how each of the main addictive drugs activates the dopamine system. Although cocaine, amphetamine, opiates, alcohol, nicotine, cannabis, barbiturates, and benzodiazepines activate the dopamine system, they do so to different degrees. Caffeine at high doses activates the dopamine system but has its own intracellular, dopamine-like, low-dose effects. High-energy foods, and perhaps the thrills of gambling, also activate the dopamine system and do so at levels that should cause burst responding.

Cocaine

Cocaine is a psychomotor stimulant. Cocaine and amphetamine are differentiated from the traditional stimulants strychnine, pentylenetetrazol, and picrotoxin that produce convulsions and are not addictive. Cocaine elevates extracellular dopamine levels (Di Chiara & Imperato 1988) and is habit-forming (Deneau et al. 1969). It causes a form of euphoria that overlaps with amphetamine euphoria but is quite distinct from the euphoria attributed to other drugs. Cocaine's stimulant effect increases behavior and mood and alleviates boredom and fatigue (Jones 1984).

Cocaine activates the dopamine system by blocking the reuptake of dopamine by the dopamine transporter, a molecule expressed by dopaminergic neurons. It also blocks the uptake of two other neurotransmitters: norepinephrine and serotonin. Cocaine has aversive as well as rewarding effects; its aversive effects may be due to cocaine's blockade of the norepinephrine or serotonin transporter. Correlates of the aversive events, including activation of their predictors, are relayed to the lateral habenula nucleus, which trans-synaptically inhibits the dopamine system (Jhou et al. 2013). Of the various projections of the dopamine system the projection to the dorsal striatum seems most important for habit formation (Szczypka et al. 2001, Yin et al. 2004).

Cocaine elevates basal dopamine levels severalfold, as measured by microdialysis (Di Chiara & Imperato 1988). At self-administered doses, it elevates baseline striatal dopamine three- to fivefold (Ito et al. 2000, 2002; Weiss et al. 1992, Wise et al. 1995b). Cocaine makes accumulating peaks from burst firing (as measured by FSCV) more visible, driving peaks well above the 20-nM threshold in treated animals (Stuber et al. 2005). If dopamine systems are lesioned, then rats continue to respond for apomorphine (a postsynaptic dopamine agonist) but lose their willingness to respond for cocaine (a dopamine uptake inhibiter) (Roberts et al. 1977). Low doses of dopamine receptor antagonists cause rats to increase their response rate, taking more than normal doses of cocaine per hour; when high doses of antagonists are given, the rewarding effect of cocaine is blocked (de Wit & Wise 1977, Ettenberg et al. 1982). Within binges of cocaine self-administration, rats respond to the next injection whenever their extracellular dopamine levels fall to a threshold approximately double their normal baseline level (Wise et al. 1995b).

Cocaine-experienced animals learn not only about the rewarding effects of the drug, but also about aversive side effects of cocaine abstinence that occur with or after cocaine exposure. They learn to approach places where they have had immediate cocaine injections, and they avoid places where they have been placed 15 minutes after receiving cocaine injections (Ettenberg et al. 1999). Low doses of cocaine elicit increased 22-kHz vocalizations, indicative of aversion (Barker et al. 2014). Such aversive effects as adrenergic or serotonergic signaling may be caused directly by cocaine or its aftereffects that result from the prior wearing off of cocaine's positive effects (Wenzel et al. 2013). Rats also learn that cues paired with delayed access to cocaine are aversive (Grigson & Twining 2002, Wheeler et al. 2008). For example, the normally appetitive taste of saccharin elicits aversive behavioral reactions when it is repeatedly delivered over a 30- or 45-minute period prior to the opportunity to self-administer cocaine. By contrast, a taste cue that is paired with delayed access to saline self-administration has no such effect. The oral responses are similar to those elicited by unconditioned bitter tastes such as quinine: Rats gape and eject these solutions from their mouths. Once a taste becomes a conditioned aversive stimulus, decreasing striatal dopamine release, it has established an aversive state (Wheeler et al. 2011, 2015). It establishes a negative conditioning situation; it is relief from the aversive state—due to a cue that signals immediate cocaine—that appears to be reinforcing. The stress hormone CRF has been suggested (Baker et al. 2004, Koob 1999) as a source of the aversive state. Ventral midbrain microinjections of a CRF receptor antagonist partially block the ability of quinine to inhibit dopamine release (Twining et al. 2015). Understanding the way that cues of delayed or unavailable access modify anxiety and drug taking will be important for improving animal models of addiction, as these cues elicit behavioral responses closely aligned with those observed in human addicts (Robbins et al. 2000, Sinha 2008).

Cocaine-addicted humans develop long-term decreases in expression of D_2 dopamine receptors (Volkow et al. 1992), presumably leaving them with reduced sensitivity to nonhabitual rewards.

Amphetamines

Amphetamine, methamphetamine, and related drugs are also psychomotor stimulants. They elevate dopamine levels (Di Chiara & Imperato 1988, Gough et al. 2014) and are habit-forming (Deneau et al. 1969, Pickens & Harris 1968). As with cocaine, the direct effects of amphetamines are elevated mood, increased alertness, and relief from fatigue, and their withdrawal symptoms are depressed activity, depressed mood, and lack of motivation. Animals learn to avoid cues that predict delayed access to amphetamine (Fudala & Iwamoto 1990).

Amphetamines elevate extracellular dopamine levels by releasing dopamine from vesicles and by reversing the dopamine transporter (Jones et al. 1998, Sulzer et al. 1995). Amphetamine causes rapid dopamine release. In a typical self-administration experiment, baseline dopamine is elevated several-fold (Ranaldi et al. 1999), accompanied by phasic dopamine release (Daberkow et al. 2013). Low doses of dopamine receptor antagonists cause increased amphetamine intake; high doses cause extinction responding (Wise et al. 1976, Yokel & Wise 1975).

As with cocaine-addicted individuals, methamphetamine-addicted humans develop long-term decreases in expression of D_2 dopamine receptors (Schrantee et al. 2015, Volkow et al. 2001), presumably leaving them with reduced sensitivity to nonhabitual rewards.

Opiates

Opiates including morphine, heroin, codeine, fentanyl, and oxycodone are sedative hypnotics that indirectly (Johnson & North 1992) elevate dopamine levels (Di Chiara & Imperato 1988, Vander Weele et al. 2014), decrease tension and pain, and are habit-forming (Deneau et al. 1969). These drugs cause euphoria different from the euphoric effects of cocaine or amphetamine but with some degree of overlap with those caused by alcohol, benzodiazepines, and barbiturates (Kalant 1977).

Opiates have three classes of receptors. Actions at the μ-opioid receptor, localized to the ventral tegmental area, are primary for the habit-forming effects of opiates (Bozarth & Wise 1981, Broekkamp et al. 1976). Rats will lever press for microinjections of the selective μ-agonist DAMGO ([D-ALA^2, N-Me-Phe^4-Gly^5-ol]-enkephalin) to this region, where it is two orders more effective than the ∂-agonist DPDPE ([D-Pen^2,D-Pen^5]-enkephalin) (Devine & Wise 1994). These compounds disinhibit the dopamine system with the same relative difference in potencies (Devine et al. 1993). Endogenous μ-opioid endomorphin-1 is self-administered into this region (Zangen et al. 2002). Heroin is preferred for intravenous use. It enters the brain more quickly than does morphine, is quickly metabolized (losing its two acetyl groups), and becomes morphine as it enters the brain. It is self-administered and elevates dopamine levels to approximately the same extent as cocaine (Wise et al. 1995a).

The mechanism by which opiates activate the dopamine system is trans-synaptic. It inhibits GABA-containing neurons that, in turn, normally hold the dopamine neurons under inhibitory control (Sugita et al. 1992). Thus, morphine disinhibits the dopamine system (Johnson & North 1992) by an action on these (Johnson & North 1992) or nearby GABA neurons (Ikemoto et al. 1997, Jhou et al. 2012, Liu & Ikemoto 2007). The most recent evidence suggests that heroin selectively disinhibits a medial subgroup of dopamine neurons that project to the medial shell of the ventral striatum (Corre et al. 2018).

Mice learn not only to approach cues that predict reward, but also to avoid cues that predict conditions where opiates will not be available (Zhu et al. 2016). Opiates have multiple behavioral effects: They alleviate pain (Tung & Yaksh 1982), stimulate feeding (Pecina & Berridge 2005), and alleviate social distress (Herman & Panksepp 1978). They have at least two forms of direct aversive effects. First, they have direct aversive opiate effects in the periphery (Bechara & van der Kooy

1985) mediated by the κ-opioid receptor. Second, they have aversive effects at κ-opioid receptors within the brain (Bals-Kubik et al. 1989, Hawes et al. 2017).

As with cocaine- and methamphetamine-addicted users, opiate-addicted humans develop long-term decreases in expression of D_2 dopamine receptors (Wang et al. 1997), presumably leaving them with reduced sensitivity to nonhabitual rewards.

Alcohol

Alcohol is a depressant drug, but at low doses and early during intoxication, it elevates striatal dopamine levels and is habit-forming. The immediate effects of low doses or early intoxication are euphoria and a decrease in inhibitions; when higher doses are taken, depression is experienced.

Alcohol activates the dopamine system (Di Chiara & Imperato 1986). Self-administered doses increase resting dopamine levels by approximately 50% over normal baseline in alcohol-preferring rats (Weiss et al. 1992). Alcohol causes minor increases in baseline dopamine levels. However, FSCV reveals alcohol-induced dopamine peaks, the product of dopaminergic burst firing, in some striatal subregions (Robinson et al. 2009), but the mechanisms by which it does so are not well understood (Abrahao et al. 2017). Unlike other addictive drugs, it has no receptor and thus does not have a single or simple mechanism of action. It binds to several ion channels on multiple receptors. A strong possibility is that the ability of alcohol to activate the dopamine system depends on interactions with glycine receptors that interact with GABA receptors in the ventral striatum or ventral tegmental area (Söderpalm et al. 2017). Alcohol may also activate the reward system by activating serotonin-3 receptors (McBride et al. 2004) on dopaminergic neurons (Wang et al. 2019). Alcohol self-administration is also reduced by mecamylamine, a nicotinic receptor blocker (Ericson et al. 1998), suggesting alcohol has multiple sites of rewarding action.

Although the taste of alcoholic beverages is usually aversive to new users, alcohol-associated cues cause persistent craving, anxiety, and behavioral distress in experienced users (Sinha et al. 2009). As with habitual cocaine-, methamphetamine-, and opiate-addicted users, alcoholic humans develop long-term decreases in expression of D_2 dopamine receptors (Volkow et al. 2017, Yoder et al. 2016), presumably leaving them with reduced sensitivity to nonhabitual rewards.

Nicotine

Nicotine is a psychomotor stimulant that causes burst firing of dopamine neurons (Grenhoff et al. 1986), elevates extracellular dopamine levels (Di Chiara & Imperato 1988, Doyon et al. 2013, Fu et al. 2000), and is habit-forming (Cohen & Ettenberg 2007, Corrigall et al. 1992, Donny et al. 1995). It acts at a subset of acetylcholine receptors in the brain, with actions in both the ventral tegmental area (Picciotto et al. 1998) and striatum (Jones et al. 2001, Reuben & Clarke 2000).

Nicotine acts at subsets of acetylcholine receptors that are expressed in many brain regions; different subsets are composed of different subunit combinations (McGehee & Role 1995). The primary nicotinic dopamine-elevating action involves receptors localized in the medial portion of the ventral tegmental area (Ikemoto et al. 2006, Miller et al. 2005, Picciotto et al. 1998), but it can also act at receptors in the striatum (Mifsud et al. 1989). Each of these receptor groups regulates the release of dopamine from dopaminergic axon terminals (Champtiaux & Changeux 2004, Salminen et al. 2004). Nicotine causes dopaminergic neurons to discharge, and nicotinic effects in the striatum involve a mixture of effects that influence release of dopamine from axon terminals (Rice & Cragg 2004, Windels & Kiyatkin 2003, Zhang & Sulzer 2004). Cigarette smoking also increases dopamine levels through non-nicotinic substances by inhibiting the catabolic enzyme monoamine oxidase (Smith et al. 2016).

Although nicotine is rewarding, its prominent subjective effect for new users is aversive. If nicotine is given after a 20-minute delay, the cues that were present during the delay become aversive (Fudala & Iwamoto 1987).

As with habitual cocaine-, methamphetamine-, opiate-, and alcohol-addicted users, nicotine-addicted humans develop long-term decreases in expression of D_2 dopamine receptors (Fehr et al. 2008), presumably leaving them with reduced sensitivity to nonhabitual rewards.

Marijuana

The addictive agent in marijuana is Δ^9-tetrahydrocannabinol (Δ^9-THC). It is a depressant and causes relaxation and a form of euphoria that overlaps to some extent with, but is clearly different from, opioid euphoria. It acts at cannabinoid receptors in the brain (Matsuda et al. 1990), is habit-forming (Curran et al. 2016, Gardner & Lowinson 1991), and elevates extracellular dopamine levels (Chen et al. 1990, Lupica & Riegel 2005, Oleson & Cheer 2012). THC also increases dopamine signaling in the human striatum (Bossong et al. 2009). The growth of marijuana for human use has become complicated by recent changes in legislation and by the high concentrations of Δ^9-THC that have recently become available. Because of delay of absorption, awareness that an overdose has been taken orally is likely to be more impaired that when the substance is smoked.

CB1 and CB2 are receptors for the two endogenous cannabinoids anandamide and 2-arachidonoylglycerol that function as retrograde neurotransmitters. They have an atypical mechanism of action. They are synthesized and released by dopaminergic neurons and elsewhere, and they act presynaptically on local axon terminals (Davis et al. 2018, Mateo et al. 2017). Glutamate and GABA terminals are each targets for these transmitters; they are found near the dopamine cell bodies where they can activate dopamine neurons or inhibit local GABA cells that inhibit dopamine neurons (Freund et al. 2003, Ng Cheong Ton et al. 1988, Riegel & Lupica 2004, Sperlagh et al. 2009). The net result of cannabinoid treatment is increased burst firing of dopamine neurons (French et al. 1997) and increased dopamine efflux into the striatum and prefrontal cortex (Chen et al. 1991, Ng Cheong Ton et al. 1988, Oleson & Cheer 2012). At high doses, cannabis also acts at CB2 receptors that are expressed on dopaminergic neurons (Garcia et al. 2016, Spiller et al. 2019). Not only are cannabinoids rewarding, but pharmacological blockade of the CB1 cannabinoid receptor also inhibits the rewarding effects of nicotine, ethanol, morphine, heroin (Manzanares et al. 2018, Oleson & Cheer 2012), and food seeking (Abel 1975, Foltin et al. 1986, Kirkham 2005).

In rodents, abrupt cessation of THC does not produce an obvious withdrawal state. However, precipitated withdrawal via treatment with a CB1 receptor antagonist does and is associated with reduced dopamine signaling (Diana et al. 1998). The observed withdrawal symptoms in humans following THC cessation are decreased appetite, irritability, nervousness, restlessness, shakiness, sleeping difficulty, stomach pain, strange dreams, sweating, and weight loss (Budney & Hughes 2006).

As with habitual cocaine, methamphetamine, opiate, nicotine, and alcohol use, human addicts with psychotic symptoms develop long-term decreases in expression of D_2 dopamine receptors (Bloomfield et al. 2014, Fehr et al. 2008). With an unusually sensitive assay, cannabis users without such symptoms have downregulated D_2 receptors (van de Giessen et al. 2017), presumably leaving them with reduced sensitivity to nonhabitual rewards.

Barbiturates and Benzodiazepines

Barbiturates and benzodiazepines are depressants producing withdrawal symptoms that overlap with those associated with ethanol (Kalant 1977). Although their primary action is depressant, they

activate (disinhibit) the dopamine system. They elevate dopamine levels (Di Chiara & Imperato 1986, O'Brien & White 1987, Schelp et al. 2018, van der Kooij et al. 2018) and are habit-forming (Griffiths et al. 1981). The dopamine-activating effects of these drugs appear to be dose dependent; low doses cause obvious dopamine-like behavioral actions (Wise & Bozarth 1987). Abrupt withdrawal from barbiturates can also cause convulsions (Essig 1966).

Caffeine

Caffeine is a psychomotor stimulant that is habit-forming. It produces feelings of well-being, happiness, alertness, and sociability (Griffiths et al. 2003). At high doses, it can elevate dopamine levels (Acquas et al. 2002, Okada et al. 1997, Okada et al. 1996). However, at the doses humans usually consume, caffeine is minimally effective at activating the dopamine system. At low doses, it blocks the effects of adenosine at adenosine receptors that reside on dopamine-sensitive output neurons of the striatum (Ferre 2016, Fredholm et al. 1999).

Caffeine is a particularly interesting substance for addiction research. It is marginally rewarding, and despite many laboratory attempts, intravenous caffeine is not self-administered in animals. Unless questioned, most human users are not aware of its effects on mood. Caffeine potentiates the rewarding effects of alcohol and nicotine (Rezvani et al. 2013) as well as nondrug reinforcers (Sheppard et al. 2012). Caffeine blocks adenosine A_{2A} receptors and forms heteromers with D_2 dopamine receptors in D_2 striatal output neurons (Ferre et al. 2008). Furthermore, caffeine increases postsynaptic dopamine transmission by blocking adenosine A_1 receptors that form heteromers with D_1 receptors in D_1 striatal output neurons (Ferre 2016). Thus, caffeine has intracellular effects that are dopamine-like and has the potential to influence long-term potentiation and depression (Costenla et al. 2010). Withdrawal from caffeine use has clinical symptoms that overlap with those of anxiety, depression, and insomnia (Meredith et al. 2013). Acute caffeine exposure induces changes in D_2 receptor ligand binding potential in the striatum (Volkow et al. 2015), which is probably related to allosteric interactions in the A_{2A}-D_2 receptor heteromer (Bonaventura et al. 2015).

Other Forms of Addiction

When the terms "addict" and "addiction" were first borrowed from Latin, they referred generally to self-imposed habits. The terms became frequently associated with addictive drugs approximately one century ago. Today, it is widely assumed that drug addiction is the defining example of addiction, and the question has become whether habitual gambling, eating of high-energy foods, or seeking of some other potent reward qualifies as addiction.

A strong case for regeneralizing the terms comes from consideration of compulsive overeating. As with drug-seeking behaviors, food-seeking habits are lost when dopamine is depleted from the brain (Zhou & Palmiter 1995) and are restored when the ability to synthesize dopamine is restored to the dorsal striatum (Szczypka et al. 2001). Consumption of, or lever pressing for, normal lab chow doubles dopamine levels (Hernandez & Hoebel 1988); consumption of sucrose alone (Hajnal et al. 2004) or corn oil alone (Liang et al. 2006) has approximately half this effect. Food reward causes burst firing and phasic dopamine release, and it establishes long-term potentiation and depression. Motivation to feed—sensitivity to food-predictive stimuli—is controlled by phasic activation of the dopamine system. Activation is influenced by hormones that control appetite and satiety including ghrelin, GLP-1, leptin, and insulin. All these factors interact with motivation for cocaine (You et al. 2016, You et al. 2018), and some interact with motivations for drug taking (Engel & Jerlhag 2014). As with habitual cocaine, methamphetamine, opiate, nicotine, and cannabis users,

humans who overconsume high-energy foods have decreased expression of D_2 dopamine receptors (Volkow et al. 2008, Wang et al. 2001), presumably leaving them with reduced sensitivity to nonhabitual rewards.

Pathological gambling has recently been classified as an addictive disorder. Gamblers have higher rates of dopamine turnover than do nongamblers, as reflected by elevated dopamine metabolites in cerebrospinal fluid (Bergh et al. 1997). Increased dopamine signaling is correlated with increased impulsivity, a risk factor for both gambling and substance abuse disorders (Clark et al. 2012). Periods of maximal uncertainty of reward delivery cause sustained activation of the dopamine system (Fiorillo et al. 2003). Furthermore, use of dopamine receptor agonists is associated with increased gambling (Moore et al. 2014, Potenza et al. 2013). However, positron emission tomography studies of dopamine receptor binding do not show differences between pathological gamblers and healthy controls (Potenza et al. 2013). Compulsive overeating and gambling suggest that the ability to establish dominant reward-seeking habits varies across the range of reinforcing stimuli and extends beyond the drugs that have dominated the recent literature.

SUMMARY POINTS

1. The definition of addiction as a very strong habit applies to the use of cocaine, amphetamines, opiates, alcohol, nicotine, marijuana, barbiturates, benzodiazepines, caffeine, energy-rich foods, and, perhaps, gambling and other behaviors.
2. In each case, the reward activates the dopamine system, causing burst firing or the equivalent dopamine level, long-term potentiation of associations with predictive cues, and decreases in cell-surface expression of dopamine receptors.
3. This definition of addiction identifies rewards and reward-predictive cues (of motivation or aversion) as what control behavior. It also extends the definition to cases involving nondrug rewards.
4. This definition suggests that motivational level depends on the rate of pacemaker firing in the dopamine system.

FUTURE ISSUES

1. The aversion that develops to cues that predict future (but not immediate) drugs has been determined with only one kind of cue and one addictive drug. While it seems most likely that other drugs will have the same effect, this should be tested. There are likely to be differences in the rates of aversion learning in response to such cues, and between-drug comparisons should be made.
2. Do cues other than taste—do lights, sounds, or odor cues, for example—become aversive through similar conditioning?
3. How does the aversive state caused by cues for access to future drug influence subsequent drug seeking? How does the aversive taste cue instigate approach to reward-seeking cues, which involves activation of D_1 neurons and perhaps depression of D_2 neurons? One possibility is that the aversion-induced reduction in striatal dopamine causes a subsequent rebound of dopamine release that drives seeking behavior. Another possibility

is that while the dominant response is depression of dopamine release from most striatal terminals, another subset of dopamine neurons is concurrently activated by residual predictive cues and guides reinstatement.

4. How do aversive drug cues affect dopamine signaling in brain regions other than the striatum, such as the prefrontal cortex, amygdala, and hippocampus?
5. Microdialysis and fast-scan cyclic voltammetry have been used in separate experiments; they have not been used concurrently in the same animals. Concurrent measurements by the two methods—comparing resting conditions with conditions of motivation (by food deprivation or by exposure to drug-predictive cues)—should help clarify our understanding of dopamine fluctuations under low and intermediate levels of motivation.
6. How do dopamine fluctuations influence subsets of striatal output neurons? Imaging of calcium indicators should be used to further characterize the effects of dopamine concentration on subpopulations of D_1- vs D_2-expressing output neurons. The tools for this kind of analysis have only recently been developed, and such studies may already be in progress.

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LITERATURE CITED

Abel EL. 1975. Cannabis: effects on hunger and thirst. *Behav. Biol.* 15:255–81

Abrahao KP, Salinas AG, Lovinger DM. 2017. Alcohol and the brain: neuronal molecular targets, synapses, and circuits. *Neuron* 96:1223–38

Acquas E, Tanda G, Di Chiara G. 2002. Differential effects of caffeine on dopamine and acetylcholine transmission in brain areas of drug-naive and caffeine-pretreated rats. *Neuropsychopharmacology* 27:182–93

Agnati LF, Guidolin D, Guescini M, Genedani S, Fuxe K. 2010. Understanding wiring and volume transmission. *Brain Res. Rev.* 64:137–59

Alhadeff AL, Rupprecht LE, Hayes MR. 2012. GLP-1 neurons in the nucleus of the solitary tract project directly to the ventral tegmental area and nucleus accumbens to control for food intake. *Endocrinology* 153:647–58

Anand BK, Brobeck JR. 1951. Hypothalamic control of food intake in rats and cats. *Yale J. Biol. Med.* 24:123–40

Baker TB, Piper ME, McCarthy DE, Majeskie MR, Fiore MC. 2004. Addiction motivation reformulated: an affective processing model of negative reinforcement. *Psych Rev*. 111:33–51

Bals-Kubik R, Herz A, Shippenberg TS. 1989. Evidence that the aversive effects of opioid antagonists and κ-agonists are centrally mediated. *Psychopharmacology* 98:203–6

Barker DJ, Root DH, Ma S, Jha S, Megehee L, et al. 2010. Dose-dependent differences in short ultrasonic vocalizations emitted by rats during cocaine self-administration. *Psychopharmacology* 211:435–42

Barker DJ, Simmons SJ, Servilio LC, Bercovicz D, Ma S, et al. 2014. Ultrasonic vocalizations: evidence for an affective opponent process during cocaine self-administration. *Psychopharmacology* 231:909–18

Bechara A, van der Kooy D. 1985. Opposite motivational effects of endogenous opioids in brain and periphery. *Nature* 314:533–34

Benveniste H. 1989. Brain microdialysis. *J. Neurochem.* 52:1667–79

Bergh C, Eklund T, Sodersten P, Nordin C. 1997. Altered dopamine function in pathological gambling. *Psychol. Med.* 27:473–75

Beutler LR, Eldred KC, Quintana A, Keene CD, Rose SE, et al. 2011. Severely impaired learning and altered neuronal morphology in mice lacking NMDA receptors in medium spiny neurons. *PLOS ONE* 6:e28168

Bindra D. 1969. The interrelated mechanisms of reinforcement and motivation, and the nature of their influence on response. *Nebr. Symp. Motiv.* 17:1–37

Blaine SK, Nautiyal N, Hart R, Guarnaccia JB, Sinha R. 2018. Craving, cortisol and behavioral alcohol motivation responses to stress and alcohol cue contexts and discrete cues in binge and non-binge drinkers. *Addict. Biol.* 24:1096–108

Bloomfield MA, Morgan CJ, Egerton A, Kapur S, Curran HV, Howes OD. 2014. Dopaminergic function in cannabis users and its relationship to cannabis-induced psychotic symptoms. *Biol. Psychiat.* 75:470–78

Bolles RC. 1972. Reinforcement, expectancy, and learning. *Psychol. Rev.* 79:394–409

Bonaventura J, Navarro G, Casado-Anguera V, Azdad K, Rea W, et al. 2015. Allosteric interactions between agonists and antagonists within the adenosine A_{2A} receptor-dopamine D_2 receptor heterotetramer. *PNAS* 112:E3609–18

Bossong MG, van Berckel BN, Boellaard R, Zuurman L, Schuit RC, et al. 2009. Δ^9-tetrahydrocannabinol induces dopamine release in the human striatum. *Neuropsychopharmacology* 34:759–66

Bozarth MA, Wise RA. 1981. Intracranial self-administration of morphine into the ventral tegmental area in rats. *Life Sci.* 28:551–55

Brischoux F, Chakraborty S, Brierley DI, Ungless MA. 2009. Phasic excitation of dopamine neurons in ventral VTA by noxious stimuli. *PNAS* 106:4894–99

Broekkamp CLE, Van den Bogaard JH, Heijnen HJ, Rops RH, Cools AR, Van Rossum JM. 1976. Separation of inhibiting and stimulating effects of morphine on self-stimulation behavior by intracerebral microinjections. *Eur. J. Pharmacol.* 36:443–46

Budney AJ, Hughes JR. 2006. The cannabis withdrawal syndrome. *Curr. Opin. Psychiatry* 19:233–38

Cagniard B, Balsam PD, Brunner D, Zhuang X. 2006. Mice with chronically elevated dopamine exhibit enhanced motivation, but not learning, for a food reward. *Neuropsychopharmacology* 31:1362–70

Campbell BA, Sheffield FD. 1953. Relation of random activity to food deprivation. *J. Comp. Physiol. Psychol.* 46:320–22

Carelli RM, Deadwyler SA. 1994. A comparison of nucleus accumbens neuronal firing patterns during cocaine self-administration and water reinforcement in rats. *J. Neurosci.* 14:7735–46

Champtiaux N, Changeux JP. 2004. Knockout and knockin mice to investigate the role of nicotinic receptors in the central nervous system. *Prog. Brain Res.* 145:235–51

Chen J, Paredes W, Lowinson JH, Gardner EL. 1990. Δ^9-tetrahydrocannabinol enhances presynaptic dopamine efflux in medial prefrontal cortex. *Eur. J. Pharmacol.* 190:259–62

Chen JP, Paredes W, Gardner EL. 1991. Chronic treatment with clozapine selectively decreases basal dopamine release in nucleus accumbens but not in caudate putamen as measured by in vivo brain microdialysis: further evidence for depolarization block. *Neurosci. Lett.* 122:127–31

Chiodo LA, Caggiula AR, Antelman SM, Lineberry CG. 1979. Reciprocal influences of activating and immobilizing stimuli on the activity of nigrostriatal dopamine neurons. *Brain Res.* 176:385–90

Chong TT, Bonnelle V, Manohar S, Veromann KR, Muhammed K, et al. 2015. Dopamine enhances willingness to exert effort for reward in Parkinson's disease. *Cortex* 69:40–46

Clark L, Stokes PR, Wu K, Michalczuk R, Benecke A, et al. 2012. Striatal dopamine D_2/D_3 receptor binding in pathological gambling is correlated with mood-related impulsivity. *NeuroImage* 63:40–46

Cohen A, Ettenberg A. 2007. Motivational effects of nicotine as measured in a runway model of drug self-administration. *Behav. Pharmacol.* 18:265–71

Cooper BR, Breese GR, Grant LD, Howard JL. 1973. Effects of 6-hydroxydopamine treatments on active avoidance responding: evidence for involvement of brain dopamine. *J. Pharmacol. Exp. Ther.* 185:358–70

Corre J, van Zessen R, Loureiro M, Patriarchi T, Tian L, et al. 2018. Dopamine neurons projecting to medial shell of the nucleus accumbens drive heroin reinforcement. *eLife* 7:e39945
Correa M, Carlson BB, Wisniecki A, Salamone JD. 2002. Nucleus accumbens dopamine and work requirements on interval schedules. *Behav. Brain Res.* 137:179–87
Corrigall WA, Franklin KBJ, Coen KM, Clarke P. 1992. The mesolimbic dopaminergic system is implicated in the reinforcing effects of nicotine. *Psychopharmacology* 107:285–89
Costenla AR, Cunha RA, de Mendonca A. 2010. Caffeine, adenosine receptors, and synaptic plasticity. *J. Alzheimer's Dis.* 20(Suppl. 1):S25–34
Cragg SJ, Rice ME. 2004. DAncing past the DAT at a DA synapse. *Trends Neurosci.* 27:270–77
Craig W. 1918. Appetites and aversions as constituents of instincts. *Biol. Bull.* 34:91–107
Creed M, Ntamati NR, Chandra R, Lobo MK, Luscher C. 2016. Convergence of reinforcing and anhedonic cocaine effects in the ventral pallidum. *Neuron* 92:214–26
Cui G, Jun SB, Jin X, Pham MD, Vogel SS, et al. 2013. Concurrent activation of striatal direct and indirect pathways during action initiation. *Nature* 494:238–42
Curran HV, Freeman TP, Mokrysz C, Lewis DA, Morgan CJ, Parsons LH. 2016. Keep off the grass? Cannabis, cognition and addiction. *Nat. Rev. Neurosci.* 17:293–306
Daberkow DP, Brown HD, Bunner KD, Kraniotis SA, Doellman MA, et al. 2013. Amphetamine paradoxically augments exocytotic dopamine release and phasic dopamine signals. *J. Neurosci.* 33:452–63
Danjo T, Yoshimi K, Funabiki K, Yawata S, Nakanishi S. 2014. Aversive behavior induced by optogenetic inactivation of ventral tegmental area dopamine neurons is mediated by dopamine D_2 receptors in the nucleus accumbens. *PNAS* 111:6455–60
Davis MI, Crittenden JR, Feng AY, Kupferschmidt DA, Naydenov A, et al. 2018. The cannabinoid-1 receptor is abundantly expressed in striatal striosomes and striosome-dendron bouquets of the substantia nigra. *PLOS ONE* 13:e0191436
de Jong JW, Afjei SA, Pollak Dorocic I, Peck JR, Liu C, et al. 2018. A neural circuit mechanism for encoding aversive stimuli in the mesolimbic dopamine system. *Neuron* 101:133–51.E7
de Wit H, Wise RA. 1977. Blockade of cocaine reinforcement in rats with the dopamine receptor blocker pimozide, but not with the noradrenergic blockers phentolamine or phenoxybenzamine. *Can. J. Psychol.* 31:195–203
Deneau G, Yanagita T, Seevers MH. 1969. Self-administration of psychoactive substances by the monkey. *Psychopharmacologia* 16:30–48
Denenberg VH, Kim DS, Palmiter RD. 2004. The role of dopamine in learning, memory, and performance of a water escape task. *Behav. Brain Res.* 148:73–78
Deroche-Gamonet V, Belin D, Piazza PV. 2004. Evidence for addiction-like behavior in the rat. *Science* 305:1014–17
Devine DP, Leone P, Pocock D, Wise RA. 1993. Differential involvement of ventral tegmental mu, delta and kappa opioid receptors in modulation of basal mesolimbic dopamine release: in vivo microdialysis studies. *J. Pharmacol. Exp. Ther.* 266:1236–46
Devine DP, Wise RA. 1994. Self-administration of morphine, DAMGO, and DPDPE into the ventral tegmental area of rats. *J. Neurosci.* 14:1978–84
Di Chiara G, Imperato A. 1986. Preferential stimulation of dopamine release in the nucleus accumbens by opiates, alcohol, and barbiturates: studies with transcerebral dialysis in freely moving rats. *Ann. N.Y. Acad. Sci.* 473:367–81
Di Chiara G, Imperato A. 1988. Drugs abused by humans preferentially increase synaptic dopamine concentrations in the mesolimbic system of freely moving rats. *PNAS* 85:5274–78
Diana M, Melis M, Gessa GL. 1998. Increase in meso-prefrontal dopaminergic activity after stimulation of CB1 receptors by cannabinoids. *Eur. J. Neurosci.* 10:2825–30
Donny EC, Caggiula AR, Knopf S, Brown C. 1995. Nicotine self-administration in rats. *Psychopharmacology* 122:390–94
Doyon WM, Thomas AM, Ostroumov A, Dong Y, Dani JA. 2013. Potential substrates for nicotine and alcohol interactions: a focus on the mesocorticolimbic dopamine system. *Biochem. Pharmacol.* 86:1181–93

Dreyer JK, Herrik KF, Berg RW, Hounsgaard JD. 2010. Influence of phasic and tonic dopamine release on receptor activation. *J. Neurosci.* 30:14273–83

Engel JA, Jerlhag E. 2014. Role of appetite-regulating peptides in the pathophysiology of addiction: implications for pharmacotherapy. *CNS Drugs* 28:875–86

Ericson M, Blomqvist O, Engel JA, Soderpalm B. 1998. Voluntary ethanol intake in the rat and the associated accumbal dopamine overflow are blocked by ventral tegmental mecamylamine. *Eur. J. Pharmacol.* 358:189–96

Essig CF. 1966. Barbiturate withdrawal in white rats. *Int. J. Neuropharmacol.* 5:105–7

Ettenberg A, Pettit HO, Bloom FE, Koob GF. 1982. Heroin and cocaine intravenous self-administration in rats: mediation by separate neural systems. *Psychopharmacology* 78:204–9

Ettenberg A, Raven MA, Danluck DA, Necessary BD. 1999. Evidence for opponent-process actions of intravenous cocaine. *Pharmacol. Biochem. Behav.* 64:507–12

Fehr C, Yakushev I, Hohmann N, Buchholz HG, Landvogt C, et al. 2008. Association of low striatal dopamine D_2 receptor availability with nicotine dependence similar to that seen with other drugs of abuse. *Am. J. Psychiatry* 165:507–14

Ferre S. 2016. Mechanisms of the psychostimulant effects of caffeine: implications for substance use disorders. *Psychopharmacology* 233:1963–79

Ferre S, Quiroz C, Woods AS, Cunha R, Popoli P, et al. 2008. An update on adenosine A_{2A}-dopamine D_2 receptor interactions: implications for the function of G protein-coupled receptors. *Curr. Pharm. Des.* 14:1468–74

Figlewicz DP, Evans SB, Murphy J, Hoen M, Baskin DG. 2003. Expression of receptors for insulin and leptin in the ventral tegmental area/substantia nigra (VTA/SN) of the rat. *Brain Res.* 964:107–15

Fiorillo CD, Tobler PN, Schultz W. 2003. Discrete coding of reward probability and uncertainty by dopamine neurons. *Science* 299:1898–902

Floresco SB, West AR, Ash B, Moore H, Grace AA. 2003. Afferent modulation of dopamine neuron firing differentially regulates tonic and phasic dopamine transmission. *Nat. Neurosci.* 6:968–73

Foltin RW, Brady JV, Fischman MW. 1986. Behavioral analysis of marijuana effects on food intake in humans. *Pharmacol. Biochem. Behav.* 25:577–82

Fox ME, Wightman RM. 2017. Contrasting regulation of catecholamine neurotransmission in the behaving brain: pharmacological insights from an electrochemical perspective. *Pharmacol. Rev.* 69:12–32

Fredholm BB, Battig K, Holmen J, Nehlig A, Zvartau EE. 1999. Actions of caffeine in the brain with special reference to factors that contribute to its widespread use. *Pharmacol. Rev.* 51:83–133

French ED, Dillon K, Wu X. 1997. Cannabinoids excite dopamine neurons in the ventral tegmentum and substantia nigra. *Neuroreport* 8:649–52

Freund TF, Katona I, Piomelli D. 2003. Role of endogenous cannabinoids in synaptic signaling. *Physiol. Rev.* 83:1017–66

Fu Y, Matta SG, Gao W, Sharp BM. 2000. Local α-bungarotoxin-sensitive nicotinic receptors in the nucleus accumbens modulate nicotine-stimulated dopamine secretion in vivo. *Neuroscience* 101:369–75

Fudala PJ, Iwamoto ET. 1987. Conditioned aversion after delay place conditioning with nicotine. *Psychopharmacology* 92:376–81

Fudala PJ, Iwamoto ET. 1990. Conditioned aversion after delay place conditioning with amphetamine. *Pharmacol. Biochem. Behav.* 35:89–92

Fulton S, Pissios P, Manchon RP, Stiles L, Frank L, et al. 2006. Leptin regulation of the mesoaccumbens dopamine pathway. *Neuron* 51:811–22

Garcia C, Palomo-Garo C, Gomez-Galvez Y, Fernandez-Ruiz J. 2016. Cannabinoid-dopamine interactions in the physiology and physiopathology of the basal ganglia. *Br. J. Pharmacol.* 173:2069–79

Gardner EL, Lowinson JH. 1991. Marijuana's interaction with brain reward systems: update 1991. *Pharmacol. Biochem. Behav.* 40:571–80

Gerfen CR, Surmeier DJ. 2011. Modulation of striatal projection systems by dopamine. *Annu. Rev. Neurosci.* 34:441–66

Gonon FG. 1988. Nonlinear relationship between impulse flow and dopamine released by rat midbrain dopaminergic neurons as studied by in vivo electrochemistry. *Neuroscience* 24:19–28

Gough B, Pereira FC, Fontes Ribeiro CA, Ali SF, Binienda ZK. 2014. Propentophylline increases striatal dopamine release but dampens methamphetamine-induced dopamine dynamics: a microdialysis study. *Neurochem. Int.* 76:109–13

Grace AA. 1991. Phasic versus tonic dopamine release and the modulation of dopamine system responsivity: a hypothesis for the etiology of schizophrenia. *Neuroscience* 41:1–24

Grace AA, Bunney BS. 1984a. The control of firing pattern in nigral dopamine neurons: burst firing. *J. Neurosci.* 4:2877–90

Grace AA, Bunney BS. 1984b. The control of firing pattern in nigral dopamine neurons: single spike firing. *J. Neurosci.* 4:2866–76

Grenhoff J, Aston-Jones G, Svensson TH. 1986. Nicotinic effects on the firing pattern of midbrain dopamine neurons. *Acta Physiol. Scand.* 128:351–58

Griffiths RR, Juliano LM, Chausmer AL. 2003. Caffeine pharmacology and clinical effects. *Princ. Addict. Med.* 3:193–224

Griffiths RR, Lukas SE, Bradford LE, Brady JV, Snell JD. 1981. Self-injection of barbiturates and benzodiazepines in baboons. *Psychopharmacology* 75:101–9

Grigson PS, Twining RC. 2002. Cocaine-induced suppression of saccharin intake: a model of drug-induced devaluation of natural rewards. *Behav. Neurosci.* 116:321–33

Hajnal A, Smith GP, Norgren R. 2004. Oral sucrose stimulation increases accumbens dopamine in the rat. *Am. J. Physiol. Regul. Integr. Comp. Physiol.* 286:R31–37

Hamid AA, Pettibone JR, Mabrouk OS, Hetrick VL, Schmidt R, et al. 2016. Mesolimbic dopamine signals the value of work. *Nat. Neurosci.* 19:117–26

Haney M, Miczek KA. 1994. Ultrasounds emitted by female rats during agonistic interactions: effects of morphine and naltrexone. *Psychopharmacology* 114:441–48

Hawes SL, Salinas AG, Lovinger DM, Blackwell KT. 2017. Long-term plasticity of corticostriatal synapses is modulated by pathway-specific co-release of opioids through κ-opioid receptors. *J. Physiol.* 595:5637–52

Hebb DO. 1949. *The Organization of Behavior*. New York: Wiley

Heien ML, Johnson MA, Wightman RM. 2004. Resolving neurotransmitters detected by fast-scan cyclic voltammetry. *Anal. Chem.* 76:5697–704

Henschen CW, Palmiter RD, Darvas M. 2013. Restoration of dopamine signaling to the dorsal striatum is sufficient for aspects of active maternal behavior in female mice. *Endocrinology* 154:4316–27

Herman BH, Panksepp J. 1978. Effects of morphine and naloxone on separation distress and approach attachment: evidence for opiate mediation of social affect. *Pharmacol. Biochem. Behav.* 9:213–20

Hernandez L, Hoebel BG. 1988. Feeding and hypothalamic stimulation increase dopamine turnover in the accumbens. *Physiol. Behav.* 44:599–606

Heusner CL, Hnasko TS, Szczypka MS, Liu Y, During MJ, Palmiter RD. 2003. Viral restoration of dopamine to the nucleus accumbens is sufficient to induce a locomotor response to amphetamine. *Brain Res.* 980:266–74

Horvitz JC. 2000. Mesolimbocortical and nigrostriatal dopamine responses to salient non-rewards. *Neuroscience* 96:651–56

Hsu TM, McCutcheon JE, Roitman MF. 2018. Parallels and overlap: the integration of homeostatic signals by mesolimbic dopamine neurons. *Front. Psychiatry* 9:410

Ikemoto S, Kohl RR, McBride WJ. 1997. $GABA_A$ receptor blockade in the anterior ventral tegmental area increases extracellular levels of dopamine in the nucleus accumbens of rats. *J. Neurochem.* 69:137–43

Ikemoto S, Panksepp J. 1996. Dissociations between appetitive and consummatory responses by pharmacological manipulations of reward-relevant brain regions. *Behav. Neurosci.* 110:331–45

Ikemoto S, Qin M, Liu ZH. 2006. Primary reinforcing effects of nicotine are triggered from multiple regions both inside and outside the ventral tegmental area. *J. Neurosci.* 26:723–30

Ilango A, Kesner AJ, Keller KL, Stuber GD, Bonci A, Ikemoto S. 2014. Similar roles of substantia nigra and ventral tegmental dopamine neurons in reward and aversion. *J. Neurosci.* 34:817–22

Ito R, Dalley JW, Howes SR, Robbins TW, Everitt BJ. 2000. Dissociation in conditioned dopamine release in the nucleus accumbens core and shell in response to cocaine cues and during cocaine-seeking behavior in rats. *J. Neurosci.* 20:7489–95

Ito R, Dalley JW, Robbins TW, Everitt BJ. 2002. Dopamine release in the dorsal striatum during cocaine-seeking behavior under the control of drug-associated cue. *J. Neurosci.* 22:6247–53

Jerlhag E, Egecioglu E, Dickson SL, Engel JA. 2011. Glutamatergic regulation of ghrelin-induced activation of the mesolimbic dopamine system. *Addict. Biol.* 16:82–91

Jhou TC, Good CH, Rowley CS, Xu SP, Wang H, et al. 2013. Cocaine drives aversive conditioning via delayed activation of dopamine-responsive habenular and midbrain pathways. *J. Neurosci.* 33:7501–12

Jhou TC, Xu SP, Lee MR, Gallen CL, Ikemoto S. 2012. Mapping of reinforcing and analgesic effects of the mu opioid agonist endomorphin-1 in the ventral midbrain of the rat. *Psychopharmacology* 224:303–12

Johnson PM, Kenny PJ. 2010. Dopamine D_2 receptors in addiction-like reward dysfunction and compulsive eating in obese rats. *Nat. Neurosci.* 13:635–41

Johnson SW, North RA. 1992. Opioids excite dopamine neurons by hyperpolarization of local interneurons. *J. Neurosci.* 12:483–88

Jones IW, Bolam JP, Wonnacott S. 2001. Presynaptic localisation of the nicotinic acetylcholine receptor β2 subunit immunoreactivity in rat nigrostriatal dopaminergic neurones. *J. Comp. Neurol.* 439:235–47

Jones RT. 1984. The pharmacology of cocaine. In *Cocaine: Pharmacology, Effects, and Treatment of Abuse*, ed. J Grabowski, pp. 34–53. Washington, DC: US Gov. Print. Off.

Jones SR, Gainetdinov RR, Wightman RM, Caron MG. 1998. Mechanisms of amphetamine action revealed in mice lacking the dopamine transporter. *J. Neurosci.* 18:1979–86

Kalant H. 1977. Comparative aspects of tolerance to, and dependence on, alchohol, barbiturates, and opiates. In *Alcohol Intoxication and Withdrawal*, ed. MM Gross, pp. 169–86. New York: Plenum

Keefe KA, Salamone JD, Zigmond MJ, Stricker EM. 1989. Paradoxical kinesia in Parkinsonism is not caused by dopamine release. Studies in an animal model. *Arch. Neurol.* 46:1070–75

Kirkham TC. 2005. Endocannabinoids in the regulation of appetite and body weight. *Behav. Pharmacol.* 16:297–313

Koob GF. 1999. Corticotropin-releasing factor, norepinephrine, and stress. *Biol. Psychiatry* 46:1167–80

Kravitz AV, Tye LD, Kreitzer AC. 2012. Distinct roles for direct and indirect pathway striatal neurons in reinforcement. *Nat. Neurosci.* 15:816–18

Kupchik YM, Brown RM, Heinsbroek JA, Lobo MK, Schwartz DJ, Kalivas PW. 2015. Coding the direct/indirect pathways by D_1 and D_2 receptors is not valid for accumbens projections. *Nat. Neurosci.* 18:1230–32

Lammel S, Ion DI, Roeper J, Malenka RC. 2011. Projection-specific modulation of dopamine neuron synapses by aversive and rewarding stimuli. *Neuron* 70:855–62

Laverty R, Taylor KM. 1970. Effects of intraventricular 2,4,5-trihydroxyphenylethylamine (6-hydroxydopamine) on rat behaviour and brain catecholamine metabolism. *Br. J. Pharmacol.* 40:836–46

Leinninger GM, Jo YH, Leshan RL, Louis GW, Yang H, et al. 2009. Leptin acts via leptin receptor-expressing lateral hypothalamic neurons to modulate the mesolimbic dopamine system and suppress feeding. *Cell Metab.* 10:89–98

Leshner AI. 1997. Addiction is a brain disease, and it matters. *Science* 278:45–47

Liang NC, Hajnal A, Norgren R. 2006. Sham feeding corn oil increases accumbens dopamine in the rat. *Am. J. Physiol. Regul. Integr. Comp. Physiol.* 291:R1236–39

Liu C, Kershberg L, Wang J, Schneeberger S, Kaeser PS. 2018. Dopamine secretion is mediated by sparse active zone-like release sites. *Cell* 172:706–18.e15

Liu ZH, Ikemoto S. 2007. The midbrain raphe nuclei mediate primary reinforcement via $GABA_A$ receptors. *Eur. J. Neurosci.* 25:735–43

Liu ZH, Shin R, Ikemoto S. 2008. Dual role of medial A10 dopamine neurons in affective encoding. *Neuropsychopharmacology* 33:3010–20

Ljungberg T, Apicella P, Schultz W. 1992. Responses of monkey dopamine neurons during learning of behavioral reactions. *J. Neurophysiol.* 67:145–63

Lodge DJ, Grace AA. 2006. The laterodorsal tegmentum is essential for burst firing of ventral tegmental area dopamine neurons. *PNAS* 103:5167–72

Lupica CR, Riegel AC. 2005. Endocannabinoid release from midbrain dopamine neurons: a potential substrate for cannabinoid receptor antagonist treatment of addiction. *Neuropharmacology* 48:1105–16

Lüscher C, Malenka RC. 2011. Drug-evoked synaptic plasticity in addiction: from molecular changes to circuit remodeling. *Neuron* 69:650–63

Manzanares J, Cabanero D, Puente N, Garcia-Gutierrez MS, Grandes P, Maldonado R. 2018. Role of the endocannabinoid system in drug addiction. *Biochem. Pharmacol.* 157:108–21

Marshall JF, Teitelbaum P. 1974. Further analysis of sensory inattention following lateral hypothalamic damage in rats. *J. Comp. Physiol. Psychol.* 86:375–95

Marshall JF, Turner BH, Teitelbaum P. 1971. Sensory neglect produced by lateral hypothalamic damage. *Science* 174:523–25

Mateo Y, Johnson KA, Covey DP, Atwood BK, Wang HL, et al. 2017. Endocannabinoid actions on cortical terminals orchestrate local modulation of dopamine release in the nucleus accumbens. *Neuron* 96:1112–26.e5

Matsuda LA, Lolait SJ, Brownstein MJ, Young AC, Bonner TI. 1990. Structure of a cannabinoid receptor and functional expression of the cloned cDNA. *Nature* 346:561–64

Mazzoni P, Hristova A, Krakauer JW. 2007. Why don't we move faster? Parkinson's disease, movement vigor, and implicit motivation. *J. Neurosci.* 27:7105–16

McBride WJ, Lovinger DM, Machu T, Thielen RJ, Rodd ZA, et al. 2004. Serotonin-3 receptors in the actions of alcohol, alcohol reinforcement, and alcoholism. *Alcohol. Clin. Exp. Res.* 28:257–67

McCutcheon JE, Ebner SR, Loriaux AL, Roitman MF. 2012. Encoding of aversion by dopamine and the nucleus accumbens. *Front. Neurosci.* 6:137

McDonald RJ, White NM. 1993. A triple dissociation of memory systems: hippocampus, amygdala, and dorsal striatum. *Behav. Neurosci.* 107:3–22

McGehee DS, Role LW. 1995. Physiological diversity of nicotinic acetylcholine receptors expressed by vertebrate neurons. *Annu. Rev. Physiol.* 57:521–46

McGregor A, Baker G, Roberts DC. 1994. Effect of 6-hydroxydopamine lesions of the amygdala on intravenous cocaine self-administration under a progressive ratio schedule of reinforcement. *Brain Res.* 646:273–78

McGregor A, Baker G, Roberts DC. 1996. Effect of 6-hydroxydopamine lesions of the medial prefrontal cortex on intravenous cocaine self-administration under a progressive ratio schedule of reinforcement. *Pharmacol. Biochem. Behav.* 53:5–9

Menegas W, Akiti K, Amo R, Uchida N, Watabe-Uchida M. 2018. Dopamine neurons projecting to the posterior striatum reinforce avoidance of threatening stimuli. *Nat. Neurosci.* 21:1421–30

Meredith SE, Juliano LM, Hughes JR, Griffiths RR. 2013. Caffeine use disorder: a comprehensive review and research agenda. *J. Caffeine Res.* 3:114–30

Mifsud J-C, Hernandez L, Hoebel BG. 1989. Nicotine infused into the nucleus accumbens increases synaptic dopamine as measured by in vivo microdialysis. *Brain Res.* 478:365–67

Mileykovskiy B, Morales M. 2011. Duration of inhibition of ventral tegmental area dopamine neurons encodes a level of conditioned fear. *J. Neurosci.* 31:7471–76

Miller AD, Forster GL, Yeomans JS, Blaha CD. 2005. Midbrain muscarinic receptors modulate morphine-induced accumbal and striatal dopamine efflux in the rat. *Neuroscience* 136:531–38

Moore TJ, Glenmullen J, Mattison DR. 2014. Reports of pathological gambling, hypersexuality, and compulsive shopping associated with dopamine receptor agonist drugs. *JAMA Intern. Med.* 174:1930–33

Nader MA, Morgan D, Gage HD, Nader SH, Calhoun TL, et al. 2006. PET imaging of dopamine D_2 receptors during chronic cocaine self-administration in monkeys. *Nat. Neurosci.* 9:1050–56

Nesbitt KM, Jaquins-Gerstl A, Skoda EM, Wipf P, Michael AC. 2013. Pharmacological mitigation of tissue damage during brain microdialysis. *Anal. Chem.* 85:8173–79

Nestler EJ. 2013. Cellular basis of memory for addiction. *Dialog Clin. Neurosci.* 15:431–43

Ng Cheong Ton JM, Gerhardt GA, Friedemann M, Etgen A, Rose GM, et al. 1988. The effects of Δ^9-tetrahydrocannabinol on potassium-evoked release of dopamine in the rat caudate nucleus: an in vivo electrochemical and in vivo dialysis study. *Brain Res.* 451:59–68

O'Brien DP, White FJ. 1987. Inhibition of non-dopamine cells in the ventral tegmental area by benzodiazepines: relationship to A10 dopamine cell activity. *Eur. J. Pharmacol.* 142:343–54

Ogawa SK, Watabe-Uchida M. 2017. Organization of dopamine and serotonin system: anatomical and functional mapping of monosynaptic inputs using rabies virus. *Pharmacol. Biochem. Behav.* 9:9–22

Okada M, Kiryu K, Kawata Y, Mizuno K, Wada K, et al. 1997. Determination of the effects of caffeine and carbamazepine on striatal dopamine release by in vivo microdialysis. *Eur. J. Pharmacol.* 321:181–88

Okada M, Mizuno K, Kaneko S. 1996. Adenosine A1 and A2 receptors modulate extracellular dopamine levels in rat striatum. *Neurosci. Lett.* 212:53–56

Oleson EB, Cheer JF. 2012. A brain on cannabinoids: the role of dopamine release in reward seeking. *Cold Spring Harb. Perspect. Med.* 2:a012229

Owesson-White CA, Roitman MF, Sombers LA, Belle AM, Keithley RB, et al. 2012. Sources contributing to the average extracellular concentration of dopamine in the nucleus accumbens. *J. Neurochem.* 121:252–62

Palmiter RD. 2008. Dopamine signaling in the dorsal striatum is essential for motivated behaviors: lessons from dopamine-deficient mice. *Ann. N.Y. Acad. Sci.* 1129:35–46

Parker JG, Zweifel LS, Clark JJ, Evans SB, Phillips PE, Palmiter RD. 2010. Absence of NMDA receptors in dopamine neurons attenuates dopamine release but not conditioned approach during Pavlovian conditioning. *PNAS* 107:13491–96

Parsons LH, Justice JB. 1992. Extracellular concentration and in vivo recovery of dopamine in the nucleus accumbens using microdialysis. *J. Neurochem.* 58:212–18

Pavlov IP. 1927. *Conditioned Reflexes*. Oxford, UK: Oxford Univ. Press

Pecina S, Berridge KC. 2005. Hedonic hot spot in nucleus accumbens shell: Where do μ-opioids cause increased hedonic impact of sweetness? *J. Neurosci.* 25:11777–86

Phillips PE, Stuber GD, Heien ML, Wightman RM, Carelli RM. 2003. Subsecond dopamine release promotes cocaine seeking. *Nature* 422:614–18

Picciotto MR, Zoli M, Rimondini R, Lena C, Marubio LM, et al. 1998. Acetylcholine receptors containing the β2 subunit are involved in the reinforcing properties of nicotine. *Nature* 391:173–77

Pickens R, Harris WC. 1968. Self-administration of d-amphetamine by rats. *Psychopharmacologia* 12:158–63

Potenza MN, Balodis IM, Franco CA, Bullock S, Xu J, et al. 2013. Neurobiological considerations in understanding behavioral treatments for pathological gambling. *Psychol. Addict. Behav.* 27:380–92

Ranaldi R, Pocock D, Zereik R, Wise RA. 1999. Dopamine fluctuations in the nucleus accumbens during maintenance, extinction, and reinstatement of intravenous D-amphetamine self-administration. *J. Neurosci.* 19:4102–9

Reuben M, Clarke PB. 2000. Nicotine-evoked [^{3}H]5-hydroxytryptamine release from rat striatal synaptosomes. *Neuropharmacology* 39:290–99

Reynolds JN, Hyland BI, Wickens JR. 2001. A cellular mechanism of reward-related learning. *Nature* 413:67–70

Rezvani AH, Sexton HG, Johnson J, Wells C, Gordon K, Levin ED. 2013. Effects of caffeine on alcohol consumption and nicotine self-administration in rats. *Alcohol Clin. Exp. Res.* 37:1609–17

Rice ME, Cragg SJ. 2004. Nicotine amplifies reward-related dopamine signals in striatum. *Nat. Neurosci.* 7:583–84

Rice ME, Cragg SJ. 2008. Dopamine spillover after quantal release: rethinking dopamine transmission in the nigrostriatal pathway. *Brain Res. Rev.* 58:303–13

Richfield EK, Penney JB, Young AB. 1989. Anatomical and affinity state comparisons between dopamine D_1 and D_2 receptors in the rat central nervous system. *Neuroscience* 30:767–77

Riegel AC, Lupica CR. 2004. Independent presynaptic and postsynaptic mechanisms regulate endocannabinoid signaling at multiple synapses in the ventral tegmental area. *J. Neurosci.* 24:11070–78

Robbins SJ, Ehrman RN, Childress AR, Cornish JW, O'Brien CP. 2000. Mood state and recent cocaine use are not associated with levels of cocaine cue reactivity. *Drug Alcohol Depend.* 59:33–42

Roberts DCS, Corcoran ME, Fibiger HC. 1977. On the role of ascending catecholaminergic systems in intravenous self-administration of cocaine. *Pharmacol. Biochem. Behav.* 6:615–20

Robinson DL, Howard EC, McConnell S, Gonzales RA, Wightman RM. 2009. Disparity between tonic and phasic ethanol-induced dopamine increases in the nucleus accumbens of rats. *Alcohol. Clin. Exper. Res.* 33:1187–96

Robinson DL, Phillips PE, Budygin EA, Trafton BJ, Garris PA, Wightman RM. 2001. Sub-second changes in accumbal dopamine during sexual behavior in male rats. *Neuroreport* 12:2549–52

Roop RG, Hollander JA, Carelli RM. 2002. Accumbens activity during a multiple schedule for water and sucrose reinforcement in rats. *Synapse* 43:223–26

Saal D, Dong Y, Bonci A, Malenka RC. 2003. Drugs of abuse and stress trigger a common synaptic adaptation in dopamine neurons. *Neuron* 37:577–82

Salamone JD, Correa M, Farrar A, Mingote SM. 2007. Effort-related functions of nucleus accumbens dopamine and associated forebrain circuits. *Psychopharmacology* 191:461–82

Salminen O, Murphy KL, McIntosh JM, Drago J, Marks MJ, et al. 2004. Subunit composition and pharmacology of two classes of striatal presynaptic nicotinic acetylcholine receptors mediating dopamine release in mice. *Mol. Pharmacol.* 65:1526–35

Sam PM, Justice JB Jr. 1996. Effect of general microdialysis-induced depletion on extracellular dopamine. *Anal. Chem.* 68:724–28

Scardochio T, Trujillo-Pisanty I, Conover K, Shizgal P, Clarke PB. 2015. The effects of electrical and optical stimulation of midbrain dopaminergic neurons on rat 50-kHz ultrasonic vocalizations. *Front. Behav. Neurosci.* 9:331

Schelp SA, Brodnik ZD, Rakowski DR, Pultorak KJ, Sambells AT, et al. 2018. Diazepam concurrently increases the frequency and decreases the amplitude of transient dopamine release events in the nucleus accumbens. *J. Pharmacol. Exp. Ther.* 364:145–55

Schrantee A, Vaclavu L, Heijtel DF, Caan MW, Gsell W, et al. 2015. Dopaminergic system dysfunction in recreational dexamphetamine users. *Neuropsychopharmacology* 40:1172–80

Schultz W. 1986. Responses of midbrain dopamine neurons to behavioral trigger stimuli in the monkey. *J. Neurophysiol.* 56:1439–61

Schultz W. 1997. Dopamine neurons and their role in reward mechanisms. *Curr. Opin. Neurobiol.* 7:191–97

Schultz W, Apicella P, Ljungberg T. 1993. Responses of monkey dopamine neurons to reward and conditioned stimuli during successive steps of learning a delayed response task. *J. Neurosci.* 13:900–13

Sheppard AB, Gross SC, Pavelka SA, Hall MJ, Palmatier MI. 2012. Caffeine increases the motivation to obtain non-drug reinforcers in rats. *Drug Alcohol Depend.* 124:216–22

Sinha R. 2008. Chronic stress, drug use, and vulnerability to addiction. *Ann. N.Y. Acad. Sci.* 1141:105–30

Sinha R, Fox HC, Hong KA, Bergquist K, Bhagwagar Z, Siedlarz KM. 2009. Enhanced negative emotion and alcohol craving, and altered physiological responses following stress and cue exposure in alcohol dependent individuals. *Neuropsychopharmacology* 34:1198–208

Smith TT, Rupprecht LE, Cwalina SN, Onimus MJ, Murphy SE, et al. 2016. Effects of monoamine oxidase inhibition on the reinforcing properties of low-dose nicotine. *Neuropsychopharmacology* 41:2335–43

Smith-Roe SL, Kelley AE. 2000. Coincident activation of NMDA and dopamine D_1 receptors within the nucleus accumbens core is required for appetitive instrumental learning. *J. Neurosci.* 20:7737–42

Söderpalm B, Lidö HH, Ericson M. 2017. The glycine receptor—a functionally important primary brain target of ethanol. *Alcohol Clin. Exp. Res.* 41:1816–30

Sotak BN, Hnasko TS, Robinson S, Kremer EJ, Palmiter RD. 2005. Dysregulation of dopamine signaling in the dorsal striatum inhibits feeding. *Brain Res.* 1061:88–96

Sperlagh B, Windisch K, Ando RD, Sylvester Vizi E. 2009. Neurochemical evidence that stimulation of CB1 cannabinoid receptors on GABAergic nerve terminals activates the dopaminergic reward system by increasing dopamine release in the rat nucleus accumbens. *Neurochem. Int.* 54:452–57

Spiller KJ, Bi GH, He Y, Galaj E, Gardner EL, Xi ZX. 2019. Cannabinoid CB1 and CB2 receptor mechanisms underlie cannabis reward and aversion in rats. *Br. J. Pharmacol.* 176:1268–81

Steinberg EE, Boivin JR, Saunders BT, Witten IB, Deisseroth K, Janak PH. 2014. Positive reinforcement mediated by midbrain dopamine neurons requires D_1 and D_2 receptor activation in the nucleus accumbens. *PLOS ONE* 9:e94771

Steinfels GF, Heym J, Strecker RE, Jacobs BL. 1983. Behavioral correlates of dopaminergic unit activity in freely moving cats. *Brain Res.* 258:217–28

Strecker RE, Jacobs BL. 1985. Substantia nigra dopaminergic unit activity in behaving cats: effect of arousal on spontaneous discharge and sensory evoked activity. *Brain Res.* 361:339–50

Stricker EM, Zigmond MJ. 1976. Recovery of function after damage to central catecholamine-containing neurons: a neurochemical model for the lateral hypothalamic syndrome. In *Progress in Psychobiology and Physiological Psychology*, ed. JM Sprague, AN Epstein, pp. 121–88. New York: Academic

Stuber GD, Roitman MF, Phillips PE, Carelli RM, Wightman RM. 2005. Rapid dopamine signaling in the nucleus accumbens during contingent and noncontingent cocaine administration. *Neuropsychopharmacology* 30:853–63

Sugita S, Johnson SW, North RA. 1992. Synaptic inputs to $GABA_A$ and $GABA_B$ receptors originate from discrete afferent neurons. *Neurosci. Lett.* 134:207–11

Sulzer D, Chen TK, Lau YY, Kristensen H, Rayport S, Ewing A. 1995. Amphetamine redistributes dopamine from synaptic vesicles to the cytosol and promotes reverse transport. *J. Neurosci.* 15:4102–8

Szczypka MS, Kwok K, Brot MD, Marck BT, Matsumoto AM, et al. 2001. Dopamine production in the caudate putamen restores feeding in dopamine-deficient mice. *Neuron* 30:819–28

Szczypka MS, Rainey MA, Kim DS, Alaynick WA, Marck BT, et al. 1999. Feeding behavior in dopamine-deficient mice. *PNAS* 96:12138–43

Tecuapetla F, Jin X, Lima SQ, Costa RM. 2016. Complementary contributions of striatal projection pathways to action initiation and execution. *Cell* 166:703–15

Thanos PK, Kim R, Delis F, Rocco MJ, Cho J, Volkow ND. 2017. Effects of chronic methamphetamine on psychomotor and cognitive functions and dopamine signaling in the brain. *Behav. Brain Res.* 320:282–90

Tung AS, Yaksh TL. 1982. In vivo evidence for multiple opiate receptors mediating analgesia in the rat spinal cord. *Brain Res.* 247:75–83

Twining RC, Wheeler DS, Ebben AL, Jacobsen AJ, Robble MA, et al. 2015. Aversive stimuli drive drug seeking in a state of low dopamine tone. *Biol. Psychiatry* 77:895–902

Ungerstedt U. 1971. Adipsia and aphagia after 6-hydroxydopamine induced degeneration of the nigro-striatal dopamine system. *Acta Physiol. Scand.* 367:95–122

van de Giessen E, Weinstein JJ, Cassidy CM, Haney M, Dong Z, et al. 2017. Deficits in striatal dopamine release in cannabis dependence. *Mol. Psychiatry* 22:68–75

van der Kooij MA, Hollis F, Lozano L, Zalachoras I, Abad S, et al. 2018. Diazepam actions in the VTA enhance social dominance and mitochondrial function in the nucleus accumbens by activation of dopamine D_1 receptors. *Mol. Psychiatry* 23:569–78

Vander Weele CM, Porter-Stransky KA, Mabrouk OS, Lovic V, Singer BF, et al. 2014. Rapid dopamine transmission within the nucleus accumbens: dramatic difference between morphine and oxycodone delivery. *Eur. J. Neurosci.* 40:3041–54

Vanderschuren LJ, Everitt BJ. 2004. Drug seeking becomes compulsive after prolonged cocaine self-administration. *Science* 305:1017–19

Volkow ND, Chang L, Wang GJ, Fowler JS, Ding YS, et al. 2001. Low level of brain dopamine D_2 receptors in methamphetamine abusers: association with metabolism in the orbitofrontal cortex. *Am. J. Psychiatry* 158:2015–21

Volkow ND, Fowler JS, Wang GJ, Hitzemann R, Logan J, et al. 1993. Decreased dopamine D_2 receptor availability is associated with reduced frontal metabolism in cocaine abusers. *Synapse* 14:169–77

Volkow ND, Hitzemann R, Wang GJ, Fowler JS, Wolf AP, et al. 1992. Long-term frontal brain metabolic changes in cocaine abusers. *Synapse* 11:184–90

Volkow ND, Wang GJ, Logan J, Alexoff D, Fowler JS, et al. 2015. Caffeine increases striatal dopamine D_2/D_3 receptor availability in the human brain. *Transl. Psychiatry* 5:e549

Volkow ND, Wang GJ, Telang F, Fowler JS, Logan J, et al. 2007. Profound decreases in dopamine release in striatum in detoxified alcoholics: possible orbitofrontal involvement. *J. Neurosci.* 27:12700–6

Volkow ND, Wang GJ, Telang F, Fowler JS, Thanos PK, et al. 2008. Low dopamine striatal D_2 receptors are associated with prefrontal metabolism in obese subjects: possible contributing factors. *NeuroImage* 42:1537–43

Volkow ND, Wiers CE, Shokri-Kojori E, Tomasi D, Wang GJ, Baler R. 2017. Neurochemical and metabolic effects of acute and chronic alcohol in the human brain: studies with positron emission tomography. *Neuropharmacology* 122:175–88

Wang B, Shaham Y, Zitzman D, Azari S, Wise RA, You A-B. 2005. Cocaine experience establishes control of midbrain dopamine glutamate and dopamine by corticotropin-releasing factor: a role in stress-induced relapse to drug seeking. *J. Neurosci.* 25:5389–96

Wang GJ, Volkow ND, Fowler JS, Logan J, Abumrad NN, et al. 1997. Dopamine D_2 receptor availability in opiate-dependent subjects before and after naloxone-precipitated withdrawal. *Neuropsychopharmacology* 16:174–82

Wang GJ, Volkow ND, Logan J, Pappas NR, Wong CT, et al. 2001. Brain dopamine and obesity. *Lancet* 357:354–57

Wang HL, Zhang S, Qi J, Wang H, Cachope R, et al. 2019. Dorsal raphe dual serotonin-glutamate neurons drive reward by establishing excitatory synapses on VTA mesoaccumbens dopamine neurons. *Cell Rep.* 26:1128–42.e7

Wardle MC, Treadway MT, Mayo LM, Zald DH, de Wit H. 2011. Amping up effort: effects of d-amphetamine on human effort-based decision-making. *J. Neurosci.* 31:16597–602

Weiss F, Hurd YL, Ungerstedt U, Markou A, Plotsky PM, Koob GF. 1992. Neurochemical correlates of cocaine and ethanol self-administration. *Ann. N.Y. Acad. Sci.* 654:220–41

Wenzel JM, Su ZI, Shelton K, Dominguez HM, von Furstenberg VA, Ettenberg A. 2013. The dopamine antagonist *cis*-flupenthixol blocks the expression of the conditioned positive but not the negative effects of cocaine in rats. *Pharmacol. Biochem. Behav.* 114–15:90–96

Westerink BHC, Damsma G, Rollema H, De Vries JB, Horn AS. 1987a. Scope and limitations of in vivo brain dialysis: a comparison of its application to various transmitter systems. *Life Sci.* 41:1763–76

Westerink BHC, Tuntler J, Damsma G, Rollema H, De Vries JB. 1987b. The use of tetrodotoxin for the characterization of drug-enhanced dopamine release in conscious rats studied by brain dialysis. *Naunyn-Schmiedeberg's Arch. Pharmacol.* 336:502–7

Wheeler DS, Robble MA, Hebron EM, Dupont MJ, Ebben AL, Wheeler RA. 2015. Drug predictive cues activate aversion-sensitive striatal neurons that encode drug seeking. *J. Neurosci.* 35:7215–25

Wheeler RA, Aragona BJ, Fuhrmann KA, Jones JL, Day JJ, et al. 2011. Cocaine cues drive opposing context-dependent shifts in reward processing and emotional state. *Biol. Psychiatry* 69:1067–74

Wheeler RA, Twining RC, Jones JL, Slater JM, Grigson PS, Carelli RM. 2008. Behavioral and electrophysiological indices of negative affect predict cocaine self-administration. *Neuron* 57:774–85

Wickens JR, Reynolds JN, Hyland BI. 2003. Neural mechanisms of reward-related motor learning. *Curr. Opin. Neurobiol.* 13:685–90

Wiers CE, Cabrera EA, Tomasi D, Wong CT, Demiral SB, et al. 2017. Striatal dopamine D_2/D_3 receptor availability varies across smoking status. *Neuropsychopharmacology* 42:2325–32

Windels F, Kiyatkin EA. 2003. Modulatory action of acetylcholine on striatal neurons: microiontophoretic study in awake, unrestrained rats. *Eur. J. Neurosci.* 17:613–22

Wise RA. 1987. Sensorimotor modulation and the variable action pattern (VAP): toward a noncircular definition of drive and motivation. *Psychobiology* 15:7–20

Wise RA, Bozarth MA. 1987. A psychomotor stimulant theory of addiction. *Psychol. Rev.* 94:469–92

Wise RA, Koob GF. 2014. The development and maintenance of drug addiction. *Neuropsychopharmacology* 39:254–62

Wise RA, Leone P, Rivest R, Leeb K. 1995a. Elevations of nucleus accumbens dopamine and DOPAC levels during intravenous heroin self-administration. *Synapse* 21:140–48

Wise RA, Newton P, Leeb K, Burnette B, Pocock P, Justice JB. 1995b. Fluctuations in nucleus accumbens dopamine concentration during intravenous cocaine self-administration in rats. *Psychopharmacology* 120:10–20

Wise RA, Yokel RA, DeWit H. 1976. Both positive reinforcement and conditioned aversion from amphetamine and from apomorphine in rats. *Science* 191:1273–75

Witten IB, Steinberg EE, Lee SY, Davidson TJ, Zalocusky KA, et al. 2011. Recombinase-driver rat lines: tools, techniques, and optogenetic application to dopamine-mediated reinforcement. *Neuron* 72:721–33

Wyvell CL, Berridge KC. 2000. Intra-accumbens amphetamine increases the conditioned incentive salience of sucrose reward: enhancement of reward "wanting" without enhanced "liking" or response reinforcement. *J. Neurosci.* 20:8122–30

Wyvell CL, Berridge KC. 2001. Incentive sensitization by previous amphetamine exposure: increased cue-triggered "wanting" for sucrose reward. *J. Neurosci.* 21:7831–40

Xiu J, Zhang Q, Zhou T, Zhou TT, Chen Y, Hu H. 2014. Visualizing an emotional valence map in the limbic forebrain by TAI-FISH. *Nat. Neurosci.* 17:1552–59

Yagishita S, Hayashi-Takagi A, Ellis-Davies GC, Urakubo H, Ishii S, Kasai H. 2014. A critical time window for dopamine actions on the structural plasticity of dendritic spines. *Science* 345:1616–20

Yin HH, Knowlton BJ, Balleine BW. 2004. Lesions of dorsolateral striatum preserve outcome expectancy but disrupt habit formation in instrumental learning. *Eur. J. Neurosci.* 19:181–89

Yoder KK, Albrecht DS, Dzemidzic M, Normandin MD, Federici LM, et al. 2016. Differences in IV alcohol-induced dopamine release in the ventral striatum of social drinkers and nontreatment-seeking alcoholics. *Drug Alcohol Depend*. 160:163–69

Yohn SE, Errante EE, Rosenbloom-Snow A, Somerville M, Rowland M, et al. 2016. Blockade of uptake for dopamine, but not norepinephrine or 5-HT, increases selection of high effort instrumental activity: implications for treatment of effort-related motivational symptoms in psychopathology. *Neuropharmacology* 109:270–80

Yokel RA, Wise RA. 1975. Increased lever pressing for amphetamine after pimozide in rats: implications for a dopamine theory of reward. *Science* 187:547–49

You ZB, Wang B, Gardner EL, Wise RA. 2018. Cocaine and cocaine expectancy increase growth hormone, ghrelin, GLP-1, IGF-1, adiponectin, and corticosterone while decreasing leptin, insulin, GIP, and prolactin. *Pharmacol. Biochem. Behav.* 176:53–56

You ZB, Wang B, Liu Q-R, Wu Y, Otvos L, Wise RA. 2016. Reciprocal inhibitory interactions between the reward-related effects of leptin and cocaine. *Neuropsychopharmacology* 41:1024–33

Yung KK, Smith AD, Levey AI, Bolam JP. 1996. Synaptic connections between spiny neurons of the direct and indirect pathways in the neostriatum of the rat: evidence from dopamine receptor and neuropeptide immunostaining. *Eur. J. Neurosci.* 8:861–69

Zangen A, Ikemoto S, Zadina JE, Wise RA. 2002. Rewarding and psychomotor stimulant effects of endomorphin-1: anterior-posterior differences within the ventral tegmental area and lack of effect in nucleus accumbens. *J. Neurosci.* 22:7225–33

Zhang H, Sulzer D. 2004. Frequency-dependent modulation of dopamine release by nicotine. *Nat. Neurosci.* 7:581–82

Zhou QY, Palmiter RD. 1995. Dopamine-deficient mice are severely hypoactive, adipsic, and aphagic. *Cell* 83:1197–209

Zhu Y, Wienecke CF, Nachtrab G, Chen X. 2016. A thalamic input to the nucleus accumbens mediates opiate dependence. *Nature* 530:219–22

Zorrilla EP, Logrip ML, Koob GF. 2014. Corticotropin releasing factor: a key role in the neurobiology of addiction. *Front. Neuroendocrinol.* 35:234–44

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