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Dopamine Across Reward, Skill, Sociality, Parenting, and Disease: A Comparative Neuroscience Review

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ABSTRACT

Dopamine is well known to be associated with reward and reinforcement learning. This review provides a detailed overview of dopamine signaling across diverse species and behavioral conditions. In stimulation experiments, dopamine activation reinforces behavior. In neural recording experiments, dopamine neurons are activated when thirsty monkeys get juice, when singing birds hit the right note, when mouse moms retrieve crying pups, and when a male bird receives affiliative feedback from a female during courtship. Together, these studies suggest that dopamine signals and reinforcement properties can generalize across many contexts. Critically, dopamine disruption in Parkinson's disease impairs the ability to initiate and control movement. Analysis of diverse neurobiological evidence reveals that while behavioral contexts vary by species, dopamine consistently functions as a flexible teaching signal that drives adaptive learning. Comparing these different models helps identify conserved features of dopamine signaling while showing how the same neural system can adapt to different behavioral demands.

INTRODUCTION

The capacity to learn from past experiences directly dictates evolutionary survival. Animals must constantly determine which behaviors lead to beneficial outcomes and which should be avoided. Whether searching for food, caring for offspring, learning a skill, or being social, organisms rely on neural evaluation systems to guide their future choices. Consequently, dopamine has historically been framed around mediating basic reward and reinforcement.

However, dopamine’s role extends beyond simple pleasure and basic reward. Investigations across various species reveal dopamine signaling during maternal care, skilled motor learning, and social interactions, suggesting that dopamine is involved in evaluating a wider range of behaviors. A breakthrough in this field revealed that dopamine neurons encode reward prediction error, the difference between an expected outcome and the actual received outcome. This discovery reframed dopamine from a basic reward transmitter to a signal that enables animals to learn from unexpectedly good or bad outcomes.

As evidence accumulates across different species and contexts, an important question remains: how does this dopamine signal adapt to evaluate such diverse behavioral demands? Comparing dopamine signaling

across species and behavioral contexts can help distinguish which aspects of the system are broadly conserved from those that are adapted to specific behaviors. This comparison offers insight into how a common neural signaling system can support different forms of learning, from basic survival behaviors to skilled performance and social interaction.

Finally, Parkinson's disease provides a complementary perspective on dopamine's role in behavior. The disease results from the gradual loss of dopamine-producing neurons and is characterized by symptoms such as slowed movement (bradykinesia) and difficulty initiating movement (akinesia). Examining what happens when dopamine signaling breaks down provides insight into how this system contributes to normal movement and behavior.

The broader implication of this research is that dopamine is not limited to a single behavioral function, but instead acts as a flexible neural signal that can support learning and adaptation across different species and behavioral contexts. Understanding which aspects of dopamine signaling are conserved and which vary across contexts may provide a clearer picture of how the brain adapts a common neural system to different behavioral demands.

METHODS

This literature review covers ten studies. Guided by an expert advisor, I used keywords such as *dopamine*, *reward prediction error*, *intracranial self-stimulation*, *optogenetics*, *dopamine fiber photometry*, *songbird vocal learning*, *maternal behavior*, *basal ganglia*, and *Parkinson's disease* to find these studies. Articles were thoroughly analyzed to determine each individual methodology, purpose, and findings and how they connected to each other.

OVERVIEW OF RESEARCH FINDINGS

1. Behavioral Reinforcement Through Electrical and Optogenetic Stimulation

1a. Electrical Stimulation as a Tool for Studying Reinforcement

Before researchers could determine how dopamine neurons contributed to reward, they first had to identify whether specific neural circuits were even capable of reinforcing behavior. Electrical brain stimulation involves passing electrical currents through small metal electrodes to local brain areas. When the electric current is generated, neurons near the electrode are briefly activated. This method provided a way to address this question by allowing researchers to directly activate targeted brain regions and observe whether animals would voluntarily seek out the stimulation. Rats could control when they received the electrical stimulation by pressing a lever, allowing researchers to measure whether they

repeatedly chose to activate a specific brain region. If rats continued pressing the lever for stimulation, this would provide evidence that activation of that region was reinforcing.

1b. Electrical Brain Stimulation Reinforces Behavior

Classical reinforcement models proposed that behavior was primarily driven by the reduction of physiological needs, such as hunger or thirst. Olds and Milner's experiments in the 1950s helped pinpoint where reinforcement signals existed (Olds & Milner, 1954). Specifically, they found that activation of specific brain regions could reinforce behavior, overriding basic survival drives. To investigate whether direct brain stimulation could serve as a reinforcer, they implanted electrodes into different target regions in rats' brains. The rats were then placed in Skinner boxes containing a lever that delivered electrode currents when pressed.

By tracking lever-pressing rates during acquisition, extinction, and re-acquisition, Olds and Milner studied whether rats would voluntarily seek out the stimulation. The electrode placement determined the strength of the reinforcement. For instance, rats with electrodes in regions such as the septal area or lateral hypothalamus exhibited extreme self-stimulation, pressing the lever to the point of exhaustion while neglecting basic needs such as food or water. Conversely, electrode placements in the visual cortex (brain region processing visual information) yielded little to no reinforcement; the rats displayed baseline behavior. Without electrical current, lever pressing declined, confirming that brain activation was the sole reinforcing agent.

These findings showed that reinforcement could arise directly from activity within specific neural circuits rather than only from satisfying physiological needs. Although Olds and Milner did not identify dopamine specifically, their work provided an important foundation for later research into dopamine's role in reinforcement (Wise, 2005). The critical advance of the Olds and Milner experiments was to clarify where in the brain reinforcement signals were generated.

1c. Optogenetic Activation of Dopamine Neurons Reinforces Place Preference

Though electrical stimulation clarifies where in the brain reinforcement signals resided, one disadvantage of electrical stimulation is its lack of specificity of cell types. Many cell types are intermingled in local brain circuits, so electrical stimulation activates all cells simultaneously. As a result, researchers cannot determine which type of neuron is responsible for the observed behavioral effects. To address this limitation, neuroscientists developed optogenetics, a technique that allows light to selectively activate defined neurons.

Optogenetics works by introducing light-sensitive proteins derived from algae called opsins into specific cell populations (Boyden et al., 2005). A commonly used opsin, called channelrhodopsin-2 (ChR2), causes neurons to fire activations when exposed to blue light. Genetic targeting combined with optical stimulation can activate a single neuron type while minimizing activation of surrounding cells.

Using this approach, Tsai and colleagues tested whether dopamine neuron activation alone could produce reinforcement (Tsai et al., 2009). They selectively expressed ChR2 in dopamine neurons in the ventral tegmental area (VTA) and inserted optical fibers into mice to deliver the light stimulation. To get the ChR2 gene specifically into dopamine neurons, they injected a virus into the VTA. The VTA drives the core circuitry of reward, motivation, and learning, a major origin point for dopamine-producing neurons in the brain. This drove the expression of the ChR2 gene, which was deliberately inserted backwards into the viral plasmid and flanked by two genetic sequences, called lox sites. Critically, their mice expressed the Cre gene specifically in dopamine neurons (and not, for example, in GABA or Glutamatergic neurons also in the VTA), as Cre was inserted into the mouse genome upstream the promoter for the gene for dopamine transferase (DAT). Though many cell types in the VTA take up the injected virus, only the dopamine neurons express the Cre gene. Thus, only dopamine neurons recognized the lox sites and flipped the gene, expressing a functional ChR2 channel. Then, when the researchers shined light over the whole VTA, only the dopamine neurons got activated. This is the key advantage of optogenetics– it allows for cell-type specific photoactivation.

Next the mice, placed into a conditioned place preference setup containing two chambers, would receive optical stimulation when entering one chamber of the two chambers. The other chamber did not produce any optical stimulation. Over repeated sessions, the mice developed a strong preference for the chamber associated with blue-light stimulation of dopamine neurons. Because the blue-light stimulation specifically targeted dopamine neurons, these findings provided stronger evidence that activation of dopamine neurons alone was sufficient to reinforce behavior. This result established dopamine as a key player in the brain's reinforcement system.

2. Neural Recordings From Dopamine Neurons Across Species

Olds and Milner and Tsai et al. demonstrate how the activation of reward-related circuits can reinforce behavior. Taken with other stimulation studies, they show that activating reward-related circuits can reinforce behavior. However, they do not reveal how dopamine neurons evaluate outcomes in real time. Therefore, researchers turned to neural recording techniques that measured dopamine activity during behavior, revealing that dopamine neurons carry information about outcomes and learning across a wide range of species and behavioral contexts.

2a. Dopamine Neurons Encode Reward Prediction Error in Monkeys

Since stimulation studies established that dopamine neurons can reinforce behavior, Schultz and colleagues aimed to test what specific information the neurons transmitted during learning by using neural recordings along with classical conditioning paradigms in monkeys to establish one of the most influential theories in modern neuroscience: that dopamine neurons encode Reward Prediction Error (RPE) hypothesis (Schultz et al, 1997).

The researchers tracked dopamine activity in the VTA and substantia nigra using precise electrophysiological recordings. The substantia nigra controls body movements and manages reward based learning. Initially, when the monkeys received unexpected juice rewards, dopamine neurons exhibited a brief burst of activity. After an association was established between sensory cues and a drop of juice, the burst in activity occurred following the reward-predicting cue, but not the reward itself. Without expected rewards, dopamine neuron activity decreased below baseline at the precise time that the predicted reward did not occur.

These results showed that dopamine neurons encode a reward prediction error– the difference between the reward received and the expected reward. Better-than-expected outcomes increased dopamine activity, expected outcomes produced little change, and worse-than-expected outcomes suppressed dopamine activity. Notably, past theoretical work proposed that an ideal learning signal would specifically occur during unexpected outcomes because if all goes as expected, the brain does not need to learn. It was therefore particularly relevant that dopamine neuron activity was so strongly gated by prediction error.

Together, the stimulation and recording studies established dopamine as an ideal teaching signal that reinforces future behavior based on unexpected reward outcomes.

2b. Dopamine Neurons Activate During Maternal Care

Building on Schultz and colleagues' findings that dopamine activity reflects differences between expected and received rewards, Xie and colleagues asked whether the same dopamine system was involved in a more complex behavior: maternal care (Xie et al., 2022). Rather than studying a basic reward such as receiving food, they examined how dopamine activity changes when female mice interact with their pups. This allowed them to test whether the same reward prediction-error framework could apply to a behavior where the outcome is not simply food but instead a positive outcome in a social setting.

The authors used fiber photometry rather than electrophysiological recordings to record dopamine signals in the female mice. In this study, the authors first injected a virus driving the expression of a gene for the fluorescent calcium indicator, GCAMP, into the VTA of mice. Using a similar approach as Tsai et al and their Cre mice, their target gene GCAMP was inserted backwards into the plasmid and flanked by lox sites. Because they injected the virus into mice expressing Cre upstream the DAT promoter, only the dopamine neurons had the capacity to flip the gene and express a functional GCAMP. Calcium increases as neural activity increases, so more GCAMP fluorescence would correlate with more dopamine activity. Using these genetic and optical methods, the authors could implant optical fibers over the VTA and measure the dopamine activity through fluorescence changes. This method is called dopamine fiber photometry.

Fiber-implanted mice were exposed to crying pups as well as control objects to allow for comparison of dopamine responses with maternal and non-social stimuli. Xie et al. found that dopamine neurons showed strong activations during pup interactions, revealing that maternal behavior engages the same reward

system that a food reward does. Furthermore, as the mothers got more used to the task of retrieving pups, and finding the pups was less and less surprising, dopamine activations decreased, suggesting dopamine signals depended on prediction error, just as with food rewards. With this, the authors were able to determine that caring for pups engages the same reward-related dopamine circuitry involved in more basic rewards discussed above to support social cues and dynamically change to shape and refine parental retrieval behavior over time.

Their results extend the RPE framework past traditional rewards such as food (when hungry) or water (when thirsty) to maternal behavior. They suggest that dopamine can help mothers learn and adjust their responses to pups by signaling changes in the expected outcome of retrieval behavior. The team posited that dopamine functions are conserved through its adaptation of signaling to different behavioral demands.

2c. Dopamine Neurons Activated When Singing Birds Hit the Right Note

The studies by Schultz and Xie illustrate dopamine signaling with both physical and socially motivated rewards and behaviors. Gadagkar and colleagues extended this work by examining a form of reward that is not reliant on external stimuli (Gadagkar et al., 2016). By looking at zebra finches, they were able to study internal skilled motor performance. Zebra finches' songs are learned and perfected through repeated practice, allowing for performance evaluation against an internal 'template', which is replicated from a tutor song heard early in life.

Individual dopamine neurons were recorded in the VTA while zebra finches sang . These electrophysiological recordings measured VTA dopamine firing projecting to Area X, a striatal brain region involved in song learning and production. Then, to manipulate the birds' self-evaluation, the team introduced distorted auditory feedback. The team could examine how dopamine activity changed when the birds' performance did not match their target expectation by causing the birds to hear brief distortions as they were singing.

Following a distorted song note, dopamine neurons decreased activity, which is consistent with a worse performance than expected. Dopamine activity increased when the song matched the target song. Importantly, these changes occurred without any external reward such as food or water. Gadagkar and colleagues therefore showed that dopamine signaling can reflect performance relative to internal standards, even without external reward. This finding extends the RPE hypothesis from external outcomes to internally generated performance evaluation.

2d. Dopamine Neurons Activated When Male Songbirds Receive Affiliative Feedback From Females

While Gadagkar et al focused on internally generated performance feedback, Roeser and colleagues explored what happened when malebirds received social feedback from a female during courtship (Roeser et al., 2023).

Dopamine fiber photometry was used to track dopamine activity while male songbirds sang either undirected songs, which occur in social isolation, or directed songs, which are sung for a female. With this, the team compared dopamine responses to song performance and to female feedback. This approach examined whether dopamine signaling remained focused on the birds' own performance or incorporated information from external social feedback.

The results revealed a clear difference. During undirected singing, dopamine activity was closely associated with song performance. The accuracy of the bird's singing compared to its own internal template of the perfect song, or the absence/presence of vocal mistakes, correlated with dopamine levels. This was consistent with the internal evaluation observed by Gadagkar and colleagues. However, during courtship, dopamine activity was more responsive to affiliative feedback from the female bird. Specifically, female vocalizations that were in sync with the male song drove enormous dopamine activations in singing males. Interestingly, when those calls were out of sync with his song these activations did not occur, suggesting that temporal alignment in the courtship interaction matters. This shift in priority suggests that social outcomes were more important to the dopamine system while actively courting a female.

Together, these findings suggest that the same dopamine signaling system can shift its focus depending on the behavioral context. During courtship, dopamine activity incorporated social feedback in addition to the bird's own performance, showing that dopamine can respond to different types of information when evaluating behavior. Combined with the above findings from Schultz, Xie, and Gadagkar, this study furthers the idea that dopamine maintains a conserved signaling framework while adapting to different behavioral demands. In all these conditions, dopamine neurons are activated following better than expected outcomes defined by what an animal 'desires' in a given moment.

3. Dopamine and the Pathophysiology of Parkinson's Disease

In addition to contributing to reinforcement learning by signaling RPE, dopamine plays an important role in movement control. Losing dopamine-producing neurons in Parkinson's disease disrupts the neural circuits that normally help initiate and regulate movement. This disruption contributes to symptoms such as bradykinesia, which includes hindered movement, and akinesia, which causes difficulty in initiating movement.

Dopamine neurons in the substantia nigra primarily target the striatum, where they influence medium spiny neurons (MSNs) involved in the basal ganglia pathways that control movement. There are two main types of MSNs: those that express dopamine receptor type 1 and type 2 (D1-MSNs and D2-MSNs, respectively). D1 receptor-expressing MSNs are activated by dopamine and form part of the direct pathway. This direct pathway reduces inhibitory basal ganglia output and promotes movement. D2 receptor-expressing MSNs, however, form part of the indirect pathway, which increases movement inhibition. Dopamine promotes movement by activating the D1 pathway while suppressing the D2 pathway (DeLong, 1990). When dopamine-producing neurons are lost, direct pathway activity decreases while the indirect pathway becomes more active. Increased activity in the indirect pathway increases inhibitory output from the basal ganglia, making movement harder.

This provides an important contrast to the earlier studies in this review. While the previous experiments examined how dopamine activity helps animals learn from and respond to different outcomes, Parkinson's disease shows what happens when dopamine signaling is disrupted. The resulting changes in striatal circuits help explain the motor deficits associated with dopamine loss. Kravitz and colleagues tested this relationship by selectively activating D1- and D2-expressing MSNs in mice to determine how each population influences basal ganglia activity and movement.

3.1. Optogenetic Activation of Striatal Neurons Restores Movement in Parkinsonian Mice

Kravitz and colleagues set out to determine which striatal circuits were responsible for the motor deficits associated with Parkinson's (Kravitz et al., 2010). Using genetic targeting and optogenetics, they selectively activated D1- and D2-MSNs in the striatum. By stimulating the populations separately, comparisons could be made between their effects on movement.

Activation of D2-expressing MSNs produced a Parkinsonian-like state, including increased freezing, slower movement, and fewer movement initiations. In contrast, activating D1-expressing MSNs increased locomotion and reduced freezing. These opposing effects provided experimental evidence that the two pathways influence motor behavior differently.

The team then replicated Parkinson's disease in mice using 6-hydroxydopamine (6-OHDA), a neurotoxin that selectively damages dopamine-producing neurons. This produced dopamine depletion and Parkinsonian motor deficits, allowing the authors to test whether activating D1-expressing MSNs could restore movement. When the team optogenetically activated D1-expressing MSNs in these mice, the animals showed a strong recovery in movement, including reduced freezing, improved locomotor initiation, and increased locomotion.

Kravitz's results provide evidence that the striatal pathways affected by dopamine loss play a central role in Parkinsonian movement deficits. They show that increasing activity in the D1 pathway can overcome some of the motor consequences of dopamine depletion. Combined with earlier work on dopamine and

the basal ganglia, it's proposed that changes in dopamine signaling can alter specific neural circuits responsible for movement.

DISCUSSION

Across studies in rodents, primates and songbirds, a common pattern emerges: dopamine does not appear to represent one specific type of reward or behavior. Instead, dopamine's activity changes according to what the animal is learning or evaluating. The stimulation studies establish that dopamine-related circuits can reinforce behavior, while the recording studies show that dopamine activity reflects differences between expected and actual outcomes. The studies of maternal care, skilled singing performance, and courtship further suggest that this basic framework can be adapted to social and internally generated forms of feedback. Parkinson's disease provides a different perspective, showing how disrupting dopamine signaling affects the circuits needed for movement. Taken together, these findings suggest that dopamine provides an adaptable system for connecting experience with future behavior (Fig. 1).



Figure 1: (A) Dopamine neurons signal better-than and worse-than predicted reward outcomes with phasic activations (blue) and suppressions (red). These signals control striatal plasticity to reinforce or extinguish past actions.

Limitations and Caveats

Much of the research in this review was done in non-human primates, rodents and songbirds, whose brains and behaviors differ from those of humans. Dopamine activity during song learning in a zebra finch may follow a similar pattern to human skill learning, but the two behaviors are not directly equivalent. Because of these differences, findings from animal models may need to be validated in humans, though this is difficult due to ethical considerations: the invasive nature of these experiments involving virus injection and neurosurgical implants of foreign devices such as electrodes and optical fibers.

It can be difficult to separate the different purposes of dopamine. Dopamine is involved in motivation, movement, and behavioral learning, so a change in dopamine activity may reflect in more than one process at the same time. Parkinson's disease makes this especially clear because dopamine loss affects

movement, but dopamine is also involved in motivation and other social, maternal, and physical behaviors.

Open Questions

The studies in this review mainly focus on observed behaviors, like drinking, singing, maternal care, courtship, and movement. Dopamine is also linked to more complicated processes and disorders, including schizophrenia. However, it is much harder to study dopamine's role in more abstract areas, such as thoughts, emotions, and perception, using animal models. It remains unclear whether the same patterns seen in reward and behavioral learning also apply to these more complex cognitive functions.

Across these studies, a common pattern emerges: dopamine does not appear to represent one specific type of reward or behavior. Instead, dopamine's activity changes according to what the animal is learning or evaluating. The stimulation studies establish that dopamine-related circuits can reinforce behavior, while the recording studies show that dopamine activity reflects differences between expected and actual outcomes. The studies of maternal care, skilled singing performance, and courtship further suggest that this basic framework can be adapted to social and internally generated forms of feedback. Parkinson's disease provides a different perspective, showing how disrupting dopamine signaling affects the circuits needed for movement. Taken together, these findings suggest that dopamine provides an adaptable system for connecting experience with future behavior.

CONCLUSION

Dopamine has often been described as part of the brain's reward system, but the various behavioral paradigms looked at in this paper suggest a broader role. Across monkeys, mice, and songbirds, dopamine activity changes as animals respond to rewards, evaluate their own performance, care for offspring, and respond to social feedback. While these behaviors are very different, all use a common framework in which dopamine helps evaluate outcomes and guide future behavior. Parkinson's disease further shows how important this system is, as when dopamine-producing neurons are lost, changes in striatal circuits can make even basic movements difficult.

Overall, dopamine appears to function as a flexible teaching signal rather than a signal linked to one specific behavior. Its basic signaling framework is conserved across species, while the information it evaluates can change depending on the situation. From finding food to learning a skill, caring for offspring, responding to social feedback, or initiating movement, dopamine helps connect past experience with future behavior.

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