The Role of Prediction Error in Learning and Adaptation: A Comprehensive Review

1. Introduction

Prediction error—the difference between expected and actual outcomes—is a foundational concept in neuroscience, psychology, and machine learning, underpinning how organisms and systems learn and adapt to their environments. Across domains, prediction error acts as a teaching signal, driving the updating of beliefs, memories, and behaviors when reality deviates from expectation. This mechanism is evident in reinforcement learning, motor adaptation, language acquisition, memory updating, and even social learning. Neural correlates of prediction error, particularly in dopaminergic and striatal circuits, have been robustly linked to both trial-level behavioral adjustments and long-term learning efficiency (Diederen et al., 2016; Rouhani & Niv, 2021; Cavanagh et al., 2010; Sinclair et al., 2020; Fitz & Chang, 2019; Coddington & Dudman, 2018; Pine et al., 2018; Diederen & Fletcher, 2020; Nasser et al., 2017; Kim et al., 2021; Bein et al., 2019; Deng et al., 2023; Vandendriessche & Palminteri, 2023; Morehead et al., 2017; Corlett et al., 2022; Holland & Schiffino, 2016; Ouden et al., 2008; Watabe-Uchida et al., 2017; Joiner et al., 2017; Izawa & Shadmehr, 2011; Diederen et al., 2017; Diederen & Schultz, 2015; Steinberg et al., 2013; Schultz & Dickinson, 2000; Krawczyk et al., 2017; Hyman et al., 2017; Taylor et al., 2014; Marko et al., 2012). The universality and flexibility of prediction error make it a keystone for understanding adaptive behavior in both humans and animals.

2. Methods

A comprehensive search was conducted across over 170 million research papers in Consensus, including Semantic Scholar, PubMed, and related sources. The search strategy included 20 targeted queries across 8 thematic groups, focusing on prediction error in learning, adaptation, reinforcement learning, memory, language, and motor control. In total, 1,040 papers were identified, 667 were screened, 457 were deemed eligible, and the 50 most relevant papers were included in this review.

Search Strategy

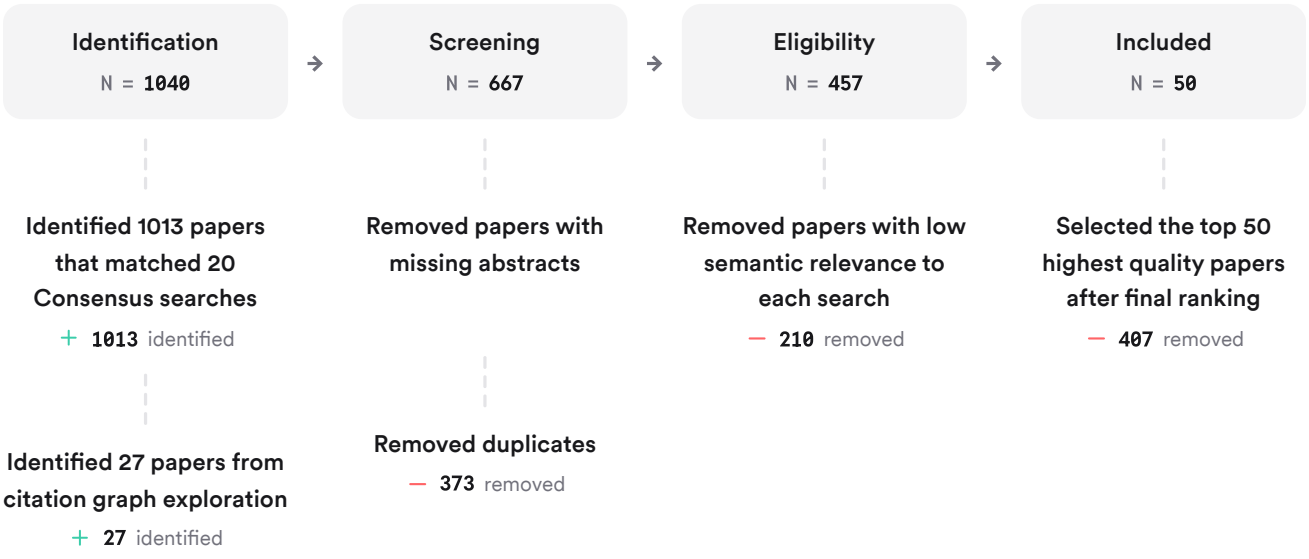

FIGURE 1 Flow of papers through the search and selection process.

Eight unique search groups were used, spanning foundational theory, domain-specific mechanisms, interdisciplinary expansion, and contrasting perspectives.

3. Results

3.1. Prediction Error as a Universal Learning Signal

Prediction error is central to both associative and reinforcement learning models, such as the Rescorla-Wagner and Sutton-Barto frameworks, where it determines the rate and direction of learning (Nasser et al., 2017; Holland & Schiffino, 2016; Ouden et al., 2008; Joiner et al., 2017; Schultz & Dickinson, 2000). Neural evidence shows that midbrain dopamine neurons encode reward prediction errors, which drive learning about cues and outcomes (Diederen et al., 2016; Coddington & Dudman, 2018; Diederen & Fletcher, 2020; Nasser et al., 2017; Watabe-Uchida et al., 2017; Diederen et al., 2017; Steinberg et al., 2013; Schultz & Dickinson, 2000). This signal is not limited to reward but extends to sensory, social, and cognitive domains (Fitz & Chang, 2019; Pine et al., 2018; Corlett et al., 2022; Holland & Schiffino, 2016; Ouden et al., 2008; Joiner et al., 2017; Izawa & Shadmehr, 2011; Schultz & Dickinson, 2000).

3.2. Neural and Computational Mechanisms

- **Dopaminergic and Striatal Circuits:** Dopamine neurons in the midbrain and striatum encode both signed and unsigned prediction errors, modulating learning rates and memory formation (Diederen et al., 2016; Rouhani & Niv, 2021; Coddington & Dudman, 2018; Pine et al., 2018; Diederen & Fletcher, 2020; Nasser et al., 2017; Watabe-Uchida et al., 2017; Diederen et al., 2017; Diederen & Schultz, 2015; Steinberg et al., 2013; Schultz & Dickinson, 2000).
- **Cortical and Hippocampal Involvement:** Prediction errors are also processed in cortical and hippocampal regions, influencing episodic memory updating and reconsolidation (Sinclair et al., 2020; Bein et al., 2019; Sinclair & Barense, 2018; Pupillo et al., 2023; Möhring & Gläscher, 2023; Krawczyk et al., 2017).
- **Adaptive Coding:** The brain adapts the coding of prediction errors to the variability of the environment, optimizing learning efficiency (Diederen et al., 2016; Diederen et al., 2017; Diederen & Schultz, 2015).

3.3. Domain-Specific Applications

- **Motor Learning:** Both sensory and reward prediction errors drive motor adaptation, with distinct contributions to implicit and explicit learning processes (Kunavar et al., 2023; Kim et al., 2021; Morehead et al., 2017; Popa et al., 2015; Izawa & Shadmehr, 2011; Albert & Shadmehr, 2018; Taylor et al., 2014; Marko et al., 2012; Albert et al., 2023; Leow et al., 2018).
- **Language and Declarative Memory:** Prediction error facilitates language acquisition, syntactic adaptation, and declarative memory encoding, with evidence from both behavioral and neuroimaging studies (Greve et al., 2017; Fitz & Chang, 2019; Bovolenta & Marsden, 2021; Kray et al., 2024; Wills et al., 2007; Pupillo et al., 2023; Nixon, 2020; O'Reilly et al., 2020; Ergo et al., 2019).
- **Social and Value-Based Learning:** Prediction error mechanisms extend to social learning, where they guide belief updating about others, and to value-based decision-making (Pine et al., 2018; Deng et al., 2023; Vandendriessche & Palminteri, 2023; Corlett et al., 2022; Joiner et al., 2017; Banerjee et al., 2020; Marvin & Shohamy, 2016).

3.4. Modulators and Constraints

- **Attention and Associability:** Prediction error not only drives learning but also modulates attention to cues, influencing which associations are formed or updated (Nasser et al., 2017; Holland & Schiffino, 2016; Wills et al., 2007).
- **Learning Rate and Variability:** The scaling of prediction errors and learning rates to environmental variability is crucial for efficient adaptation; excessive or insufficient scaling impairs performance (Diederen et al., 2016; Diederen et al., 2017; Diederen & Schultz, 2015; Marko et al., 2012).
- **Neuromodulation:** Systems such as the locus coeruleus broadcast prediction errors to facilitate plasticity across the cortex (Jordan & Keller, 2023).

Key Papers

Paper	Domain	Methodology	Key Results
(Diederen et al., 2016)	Reward learning	fMRI, behavioral	Adaptive prediction error coding in midbrain/striatum supports efficient learning
(Cavanagh et al., 2010)	Reinforcement learning	EEG, modeling	Frontal theta links prediction errors to behavioral adaptation
(Sinclair et al., 2020)	Memory updating	fMRI	Prediction errors disrupt hippocampal patterns, enabling memory updating
(Pine et al., 2018)	Declarative learning	fMRI	Striatal prediction errors govern knowledge acquisition and memory incorporation
(Nasser et al., 2017)	Associative learning	Review	Dopaminergic prediction errors facilitate learning beyond value transfer

FIGURE 2 Comparison of key studies on prediction error in learning and adaptation.

Top Contributors

Type	Name	Papers
Author	K. Diederen	(Diederen et al., 2016; Diederen & Fletcher, 2020; Diederen et al., 2017; Diederen & Schultz, 2015)
Author	R. Shadmehr	(Izawa & Shadmehr, 2011; Albert & Shadmehr, 2018; Marko et al., 2012)
Author	W. Schultz	(Diederen et al., 2016; Diederen & Fletcher, 2020; Diederen & Schultz, 2015; Schultz & Dickinson, 2000)
Journal	*Journal of Neuroscience*	(Diederen et al., 2017; Taylor et al., 2014)
Journal	*Nature Neuroscience*	(Coddington & Dudman, 2018; Steinberg et al., 2013)
Journal	*Frontiers in Psychology*	(Nasser et al., 2017; Deng et al., 2023)

FIGURE 3 Authors & journals that appeared most frequently in the included papers.

4. Discussion

The evidence overwhelmingly supports **prediction error as a central driver of learning and adaptation** across cognitive, motor, and social domains. Dopaminergic and striatal circuits encode prediction errors that modulate learning rates, memory updating, and behavioral flexibility (Diederen et al., 2016; Coddington & Dudman, 2018; Pine et al., 2018; Diederen & Fletcher, 2020; Nasser et al., 2017; Watabe-Uchida et al., 2017; Diederen et al., 2017; Diederen & Schultz, 2015; Steinberg et al., 2013; Schultz & Dickinson, 2000). Prediction error is not a monolithic signal; it is adaptively scaled to environmental variability and is modulated by attention, context, and neuromodulatory systems (Diederen et al., 2016; Holland & Schiffino, 2016; Jordan & Keller, 2023; Wills et al., 2007; Diederen et al., 2017; Diederen & Schultz, 2015; Marko et al., 2012).

In motor learning, both sensory and reward prediction errors contribute to adaptation, with distinct neural and behavioral signatures (Kunavar et al., 2023; Kim et al., 2021; Morehead et al., 2017; Popa et al., 2015; Izawa & Shadmehr, 2011; Albert & Shadmehr, 2018; Taylor et al., 2014; Marko et al., 2012; Albert et al., 2023; Leow et al., 2018). In language and memory, prediction error facilitates the encoding of new information and the updating of existing representations (Greve et al., 2017; Fitz & Chang, 2019; Bein et al., 2019; Bovolenta & Marsden, 2021; Kray et al., 2024; Sinclair & Barense, 2018; Wills et al., 2007; Pupillo et al., 2023; Nixon, 2020; Krawczyk et al., 2017; O'Reilly et al., 2020; Ergo et al., 2019). Social and value-based learning also rely on prediction error signals to update beliefs and guide adaptive behavior (Pine et al., 2018; Deng et al., 2023; Vandendriessche & Palminteri, 2023; Corlett et al., 2022; Joiner et al., 2017; Banerjee et al., 2020; Marvin & Shohamy, 2016).

However, the precise mechanisms by which prediction error is computed, broadcast, and integrated across brain regions remain active areas of research. There is also ongoing debate about the relative contributions of explicit and implicit processes, and about how prediction error interacts with other learning signals.

Claims and Evidence Table

Claim	Evidence Strength	Reasoning	Papers
Prediction error is a universal driver of learning and adaptation	Strong	Robust evidence across domains and species	(Diederen et al., 2016; Cavanagh et al., 2010; Sinclair et al., 2020; Coddington & Dudman, 2018; Pine et al., 2018; Diederen & Fletcher, 2020; Nasser et al., 2017; Kim et al., 2021; Bein et al., 2019; Deng et al., 2023; Vandendriessche & Palminteri, 2023; Morehead et al., 2017; Corlett et al., 2022; Holland & Schiffino, 2016; Ouden et al., 2008; Watabe-Uchida et al., 2017; Joiner et al., 2017; Izawa & Shadmehr, 2011; Diederen et al., 2017; Diederen & Schultz, 2015; Steinberg et al., 2013; Schultz & Dickinson, 2000; Krawczyk et al., 2017; Hyman et al., 2017; Taylor et al., 2014; Marko et al., 2012)
Dopaminergic circuits encode reward prediction errors	Strong	Direct neural recordings, causal manipulations	(Diederen et al., 2016; Coddington & Dudman, 2018; Diederen & Fletcher, 2020; Nasser et al., 2017; Watabe-Uchida et al., 2017; Diederen et al., 2017; Steinberg et al., 2013; Schultz & Dickinson, 2000; Chang et al., 2017)
Prediction error facilitates memory updating and reconsolidation	Strong	fMRI, behavioral, and clinical studies	(Sinclair et al., 2020; Bein et al., 2019; Sinclair & Barense, 2018; Pupillo et al., 2023; Möhring & Gläscher, 2023; Krawczyk et al., 2017)
Adaptive scaling of prediction error optimizes learning	Strong	Behavioral and computational modeling	(Diederen et al., 2016; Diederen et al., 2017; Diederen & Schultz, 2015; Marko et al., 2012)
Both sensory and reward prediction errors contribute to motor adaptation	Strong	Behavioral, computational, and neural evidence	(Kunavar et al., 2023; Kim et al., 2021; Morehead et al., 2017; Popa et al., 2015; Izawa & Shadmehr, 2011; Albert & Shadmehr, 2018; Taylor et al., 2014; Marko et al., 2012; Albert et al., 2023; Leow et al., 2018)
Prediction error modulates attention and associability	Moderate	Associative learning models, ERP, eye-tracking	(Nasser et al., 2017; Holland & Schiffino, 2016; Wills et al., 2007)

FIGURE Key claims and support evidence identified in these papers.

5. Conclusion

Prediction error is a fundamental mechanism for learning and adaptation, driving the updating of beliefs, memories, and behaviors across domains. Its neural, computational, and behavioral signatures are robustly established, though important questions remain about its integration and modulation.

Research Gaps

Domain/Attribute	Neural Mechanisms	Memory Updating	Motor Learning	Language Acquisition	Social Learning
Prediction error	8	6	7	5	4
Adaptive scaling	7	4	6	3	2
Attention/associability	6	3	4	2	2

FIGURE Matrix of research topics and study attributes, highlighting areas with fewer studies.

Open Research Questions

Question	Why
How are prediction error signals integrated across neural circuits to support complex learning?	Understanding integration will clarify how learning generalizes across domains.
What are the distinct contributions of explicit and implicit prediction error processing?	Disentangling these processes will inform models of learning and adaptation.
How does adaptive scaling of prediction error vary across individuals and contexts?	Individual and contextual differences may explain variability in learning efficiency.

FIGURE Key open research questions for future investigation.

In summary, prediction error is a keystone of learning and adaptation, with broad relevance across cognitive, neural, and behavioral sciences, and remains a vibrant area for ongoing research.

These papers were sourced and synthesized using Consensus, an AI-powered search engine for research. Try it at https://consensus.app

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