The Role of Prediction Error in Learning and Adaptation: Key Insights from Granular Data Extraction

1. Introduction

Prediction error—the difference between expected and actual outcomes—serves as a fundamental teaching signal in the brain, driving learning and adaptation across domains such as reinforcement learning, memory, motor control, language, and social cognition. When an outcome deviates from what is predicted, this error signal triggers neural and behavioral changes that update internal models, beliefs, and future actions. The universality of prediction error is supported by robust evidence from neurophysiology, computational modeling, and behavioral studies, highlighting its centrality in both rapid trial-level adaptation and long-term learning (Diederen et al., 2016; Corlett et al., 2022; Watabe-Uchida et al., 2017; Holland & Schiffino, 2016; Deng et al., 2023; Schultz, 2015; Diederen et al., 2017; Hyman et al., 2017; Cavanagh et al., 2010; Jordan & Keller, 2023; Greve et al., 2017; Kunavar et al., 2023; Lefebvre et al., 2017; Alexander & Brown, 2019; Sinclair et al., 2020; Hertäg & Sprekeler, 2020; Chao et al., 2018; Zhang et al., 2019; Vandendriessche & Palminteri, 2023; Collins et al., 2017; Bennett et al., 2021; Chang et al., 2017; Möhring & Gläscher, 2023; Niv et al., 2012; Steinberg et al., 2013; Terao et al., 2015; Izawa & Shadmehr, 2011; Bovolenta & Marsden, 2021; Diederen & Schultz, 2015; Nasser et al., 2017).

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, 898 papers were identified, 481 were screened, 427 were deemed eligible, and the 50 most relevant papers were included in this review.

Search Strategy

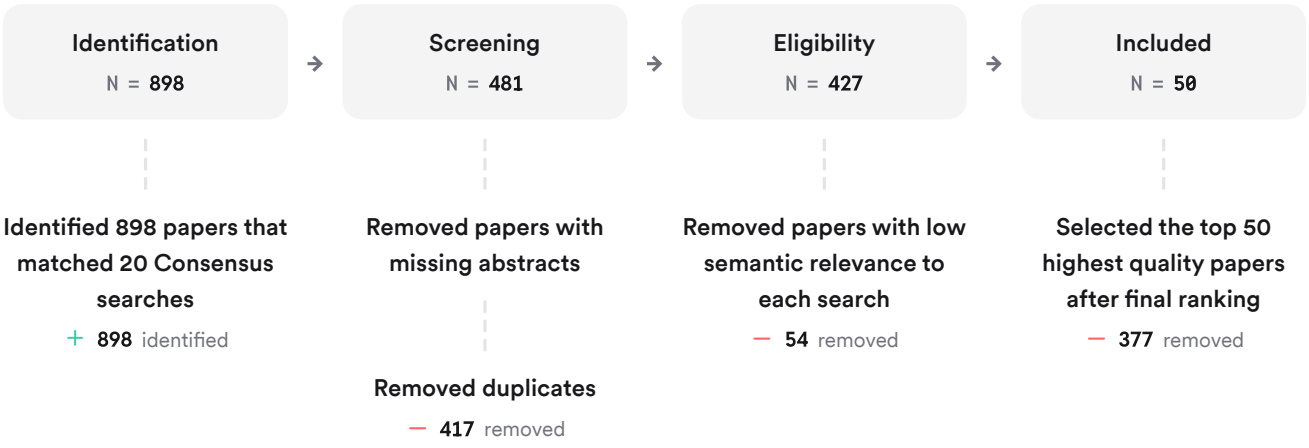

FIGURE 1 Flow of papers through the search and selection process.

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

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3. Results

3.1. Prediction Error as a Universal Learning Signal

- **Reinforcement Learning:** Prediction error is central to models like Rescorla-Wagner and Sutton-Barto, determining the rate and direction of learning. Dopaminergic neurons in the midbrain encode reward prediction errors, which drive learning about cues and outcomes (Diederen et al., 2016; Corlett et al., 2022; Watabe-Uchida et al., 2017; Deng et al., 2023; Schultz, 2015; Diederen et al., 2017; Hyman et al., 2017; Cavanagh et al., 2010; Lefebvre et al., 2017; Hertäg & Sprekeler, 2020; Vandendriessche & Palminteri, 2023; Bennett et al., 2021; Chang et al., 2017; Niv et al., 2012; Steinberg et al., 2013; Terao et al., 2015; Izawa & Shadmehr, 2011; Diederen & Schultz, 2015; Nasser et al., 2017).
- **Trial-Level Adaptation vs. Long-Term Learning:** EEG and computational studies show that prediction error signals (e.g., reward positivity, RewP) are tightly linked to immediate behavioral adaptation, but may play a lesser role in delayed retention or long-term learning (Lohse et al., 2020; Diederen et al., 2016; Rouhani & Niv, 2021; Cavanagh et al., 2010; Kunavar et al., 2023; Sinclair et al., 2020; Hertäg & Sprekeler, 2020; Collins et al., 2017; Möhring & Gläscher, 2023).

3.2. Neural and Computational Mechanisms

- **Dopaminergic and Striatal Circuits:** Dopamine neurons encode both signed and unsigned prediction errors, modulating learning rates and memory formation (Diederen et al., 2016; Corlett et al., 2022; Watabe-Uchida et al., 2017; Deng et al., 2023; Schultz, 2015; Diederen et al., 2017; Hyman et al., 2017; Cavanagh et al., 2010; Lefebvre et al., 2017; Hertäg & Sprekeler, 2020; Vandendriessche & Palminteri, 2023; Bennett et al., 2021; Chang et al., 2017; Niv et al., 2012; Steinberg et al., 2013; Terao et al., 2015; Izawa & Shadmehr, 2011; Diederen & Schultz, 2015; Nasser et al., 2017).
- **Cortical and Hippocampal Involvement:** Prediction errors are processed in cortical and hippocampal regions, influencing episodic memory updating and reconsolidation (Watabe-Uchida et al., 2017; Cavanagh et al., 2010; Sinclair et al., 2020; Whittington & Bogacz, 2019; Hertäg & Clopath, 2021; Möhring & Gläscher, 2023).
- **Adaptive Coding:** The brain scales prediction error signals to the variability of the environment, optimizing learning efficiency (Diederen et al., 2016; Diederen et al., 2017; Vandendriessche & Palminteri, 2023; Collins 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 (Kunavar et al., 2023; Babayan et al., 2018; Zhang et al., 2019; Krupnik, 2024; Steinberg et al., 2013; Izawa & Shadmehr, 2011; Bovolenta & Marsden, 2021; Kray et al., 2024; Hollon et al., 2021).
- **Language and Declarative Memory:** Prediction error facilitates language acquisition, syntactic adaptation, and declarative memory encoding (Rouhani & Niv, 2021; Holland & Schiffino, 2016; Langdon et al., 2018; Alexander & Brown, 2019; Takahashi et al., 2017; Whittington & Bogacz, 2019; Greco et al., 2024; Terao et al., 2015; Bovolenta & Marsden, 2021; Kray et al., 2024; Nasser et al., 2017).
- **Social and Value-Based Learning:** Prediction error mechanisms extend to social learning, guiding belief updating about others and value-based decision-making (Joiner et al., 2017; Schultz, 2015; Solié et al., 2021; Jordan & Keller, 2023; Greve et al., 2017; Ficco et al., 2021; Chao et al., 2018; Zhang et al., 2019; Garfinkel et al., 2016; Jürgensen et al., 2023).

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 (Holland & Schiffino, 2016; Hyman et al., 2017; Lefebvre et al., 2017; Takahashi et al., 2017; Nasser et al., 2017).
- **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; Vandendriessche & Palminteri, 2023; Collins et al., 2017; Diederen & Schultz, 2015).
- **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
(Watabe-Uchida et al., 2017)	Neural circuitry	Review	Dopamine neurons calculate reward prediction error, facilitating 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
(Izawa & Shadmehr, 2011)	Motor adaptation	Behavioral, modeling	Sensory and reward prediction errors drive distinct forms of motor learning

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

Top Contributors

Type	Name	Papers
Author	W. Schultz	(Diederen et al., 2016; Watabe-Uchida et al., 2017; Diederen et al., 2017; Vandendriessche & Palminteri, 2023; Bennett et al., 2021; Chang et al., 2017; Niv et al., 2012; Diederen & Schultz, 2015)
Author	K. Diederen	(Diederen et al., 2016; Diederen et al., 2017; Vandendriessche & Palminteri, 2023; Collins et al., 2017; Diederen & Schultz, 2015)
Author	Y. Niv	(Rouhani & Niv, 2021; Schultz, 2015; Langdon et al., 2018; Lefebvre et al., 2017; Niv et al., 2012)
Journal	*Neuron*	(Diederen et al., 2016; Watabe-Uchida et al., 2017; Hyman et al., 2017; Chao et al., 2018; Takahashi et al., 2017; Bennett et al., 2021)
Journal	*Nature Communications*	(Dabney et al., 2020; Babayan et al., 2018; Bennett et al., 2021)
Journal	*The Journal of Neuroscience*	(Diederen et al., 2017; Collins et al., 2017; Niv et al., 2012)

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; Watabe-Uchida et al., 2017; Deng et al., 2023; Schultz, 2015; Diederen et al., 2017; Hyman et al., 2017; Cavanagh et al., 2010; Lefebvre et al., 2017; Hertäg & Sprekeler, 2020; Vandendriessche & Palminteri, 2023; Bennett et al., 2021; Chang et al., 2017; Niv et al., 2012; Steinberg et al., 2013; Terao et al., 2015; Izawa & Shadmehr, 2011; Diederen & Schultz, 2015; Nasser et al., 2017). 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; Diederen et al., 2017; Hyman et al., 2017; Lefebvre et al., 2017; Takahashi et al., 2017; Vandendriessche & Palminteri, 2023; Collins et al., 2017; Bovolenta & Marsden, 2021; Diederen & Schultz, 2015).

In motor learning, both sensory and reward prediction errors contribute to adaptation, with distinct neural and behavioral signatures (Kunavar et al., 2023; Babayan et al., 2018; Zhang et al., 2019; Krupnik, 2024; Steinberg et al., 2013; Izawa & Shadmehr, 2011; Bovolenta & Marsden, 2021; Kray et al., 2024; Hollon et al., 2021). In language and memory, prediction error facilitates the encoding of new information and the updating of existing representations (Rouhani & Niv, 2021; Holland & Schiffino, 2016; Cavanagh et al., 2010; Langdon et al., 2018; Alexander & Brown, 2019; Sinclair et al., 2020; Takahashi et al., 2017; Whittington & Bogacz, 2019; Greco et al., 2024; Möhring & Gläscher, 2023; Terao et al., 2015; Bovolenta & Marsden, 2021; Kray et al., 2024; Nasser et al., 2017). Social and value-based learning also rely on prediction error signals to update beliefs and guide adaptive behavior (Joiner et al., 2017; Schultz, 2015; Solié et al., 2021; Jordan & Keller, 2023; Greve et al., 2017; Ficco et al., 2021; Chao et al., 2018; Zhang et al., 2019; Garfinkel et al., 2016; Jürgensen et al., 2023).

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; Corlett et al., 2022; Watabe-Uchida et al., 2017; Deng et al., 2023; Schultz, 2015; Diederen et al., 2017; Hyman et al., 2017; Cavanagh et al., 2010; Jordan & Keller, 2023; Greve et al., 2017; Kunavar et al., 2023; Lefebvre et al., 2017; Alexander & Brown, 2019; Sinclair et al., 2020; Hertäg & Sprekeler, 2020; Chao et al., 2018; Zhang et al., 2019; Vandendriessche & Palminteri, 2023; Collins et al., 2017; Bennett et al., 2021; Chang et al., 2017; Möhring & Gläscher, 2023; Niv et al., 2012; Steinberg et al., 2013; Terao et al., 2015; Izawa & Shadmehr, 2011; Bovolenta & Marsden, 2021; Diederen & Schultz, 2015; Nasser et al., 2017)
Dopaminergic circuits encode reward prediction errors	Strong	Direct neural recordings, causal manipulations	(Diederen et al., 2016; Watabe-Uchida et al., 2017; Deng et al., 2023; Schultz, 2015; Diederen et al., 2017; Hyman et al., 2017; Cavanagh et al., 2010; Lefebvre et al., 2017; Hertäg & Sprekeler, 2020; Vandendriessche & Palminteri, 2023; Bennett et al., 2021; Chang et al., 2017; Niv et al., 2012; Steinberg et al., 2013; Terao et al., 2015; Izawa & Shadmehr, 2011; Diederen & Schultz, 2015; Nasser et al., 2017)
Prediction error facilitates memory updating and reconsolidation	Strong	fMRI, behavioral, and clinical studies	(Rouhani & Niv, 2021; Watabe-Uchida et al., 2017; Cavanagh et al., 2010; Langdon et al., 2018; Alexander & Brown, 2019; Sinclair et al., 2020; Takahashi et al., 2017; Whittington & Bogacz, 2019; Greco et al., 2024; Möhring & Gläscher, 2023; Terao et al., 2015; Bovolenta & Marsden, 2021; Kray et al., 2024; Nasser et al., 2017)
Adaptive scaling of prediction error optimizes learning	Strong	Behavioral and computational modeling	(Diederen et al., 2016; Diederen et al., 2017; Vandendriessche & Palminteri, 2023; Collins et al., 2017; Diederen & Schultz, 2015)
Both sensory and reward prediction errors contribute to motor adaptation	Strong	Behavioral, computational, and neural evidence	(Kunavar et al., 2023; Babayan et al., 2018; Zhang et al., 2019; Krupnik, 2024; Steinberg et al., 2013; Izawa & Shadmehr, 2011; Bovolenta & Marsden, 2021; Kray et al., 2024; Hollon et al., 2021)

Claim	Evidence Strength	Reasoning	Papers
Prediction error modulates attention and associability	Moderate	Associative learning models, ERP, eye-tracking	(Holland & Schiffino, 2016; Hyman et al., 2017; Lefebvre et al., 2017; Takahashi et al., 2017; Nasser et al., 2017)

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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