Surprise and Prediction Error in Capturing Attention and Enhancing Memory: A Comprehensive Review

1. Introduction

Surprise and prediction error—defined as the mismatch between expected and actual outcomes—play a pivotal role in how attention is allocated and how memories are formed and updated. Across cognitive neuroscience, psychology, and learning theory, a robust body of research demonstrates that surprising events and prediction errors can enhance attention to relevant stimuli and promote the encoding, updating, and consolidation of memories (Rouhani & Niv, 2021; Sinclair & Barense, 2019; Sinclair et al., 2020; Kalbe & Schwabe, 2020; Lee et al., 2006; Jang et al., 2019; Antony et al., 2023; Smout et al., 2019; Sinclair & Barense, 2018; Shing et al., 2023; Ortiz-Tudela et al., 2023; Pupillo et al., 2023; Kennedy et al., 2024; Fernández et al., 2016; Nolden et al., 2024; Holland & Schiffino, 2016; Rouhani et al., 2017; Frank et al., 2020; Bein et al., 2023; Antony et al., 2020; Brod et al., 2022; Greve et al., 2017; Wills et al., 2007; Rouhani et al., 2023; Bein et al., 2021; Kafkas & Montaldi, 2018; Brod, 2021; Wahlheim et al., 2021; Sinclair et al., 2020; Jang et al., 2018; Nasser et al., 2017; Quent et al., 2021). These effects are observed in both reward-based and aversive contexts, across the lifespan, and in both laboratory and real-world settings. However, the relationship is nuanced: the magnitude, timing, and context of prediction errors, as well as individual and developmental differences, can modulate whether surprise enhances or impairs memory and attention (Nolden et al., 2025; Ortiz-Tudela et al., 2023; Pupillo et al., 2023; Liedtke et al., 2025; Decker et al., 2020; Ortiz-Tudela et al., 2021; Csink et al., 2021; Turan et al., 2024; Torrents-Rodas et al., 2023). This review synthesizes current evidence on the mechanisms by which surprise and prediction error influence attention and memory, highlighting key findings, boundary conditions, and open questions.

2. Methods

A comprehensive search was conducted across over 170 million research papers in Consensus, including Semantic Scholar, PubMed, and other databases. The search strategy involved 20 targeted queries grouped into 8 thematic clusters, focusing on prediction error, surprise, attention, memory encoding, and related neural mechanisms. In total, 1,041 papers were identified, 807 were screened, 560 were deemed eligible, and the top 50 most relevant papers were included in this review.

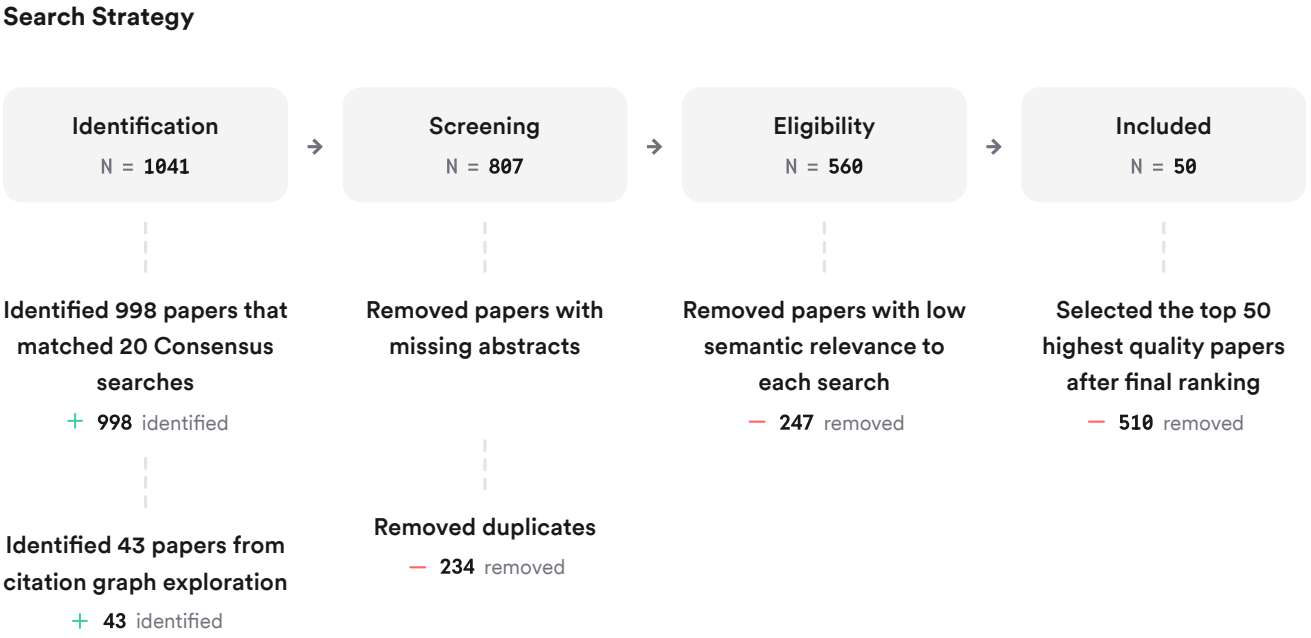

FIGURE 1 Flow diagram of the literature search and selection process.

Eight unique search groups targeted foundational theories, neural mechanisms, developmental differences, boundary conditions, and real-world applications of surprise and prediction error in attention and memory.

3. Results

3.1. Mechanisms: How Surprise and Prediction Error Capture Attention

Surprise and prediction error act as signals that direct attention to unexpected or behaviorally relevant stimuli. Neural and behavioral studies show that prediction errors, often signaled by midbrain dopamine neurons, increase the salience of cues and enhance attentional processing (Lee et al., 2006; Smout et al., 2019; Holland & Schiffino, 2016; Holland & Gallagher, 2006; Wills et al., 2007; Iordanova et al., 2021; Nasser et al., 2017). This attentional boost is critical for learning, as it prioritizes the processing of information that deviates from expectations (Smout et al., 2019; Holland & Schiffino, 2016; Wills et al., 2007; Brod, 2021; Nasser et al., 2017).

3.2. Memory Enhancement: Encoding, Updating, and Reconsolidation

Prediction errors not only capture attention but also facilitate memory encoding and updating. Surprising events are more likely to be encoded into memory, and prediction errors can trigger the reconsolidation and updating of existing memories (Rouhani & Niv, 2021; Sinclair & Barense, 2019; Sinclair et al., 2020; Kalbe & Schwabe, 2020; Jang et al., 2019; Sinclair & Barense, 2018; Shing et al., 2023; Fernández et al., 2016; Nolden et al., 2024; Rouhani et al., 2017; Frank et al., 2020; Bein et al., 2023; Antony et al., 2020; Brod et al., 2022; Greve et al., 2017; Rouhani et al., 2023; Bein et al., 2021; Kafkas & Montaldi, 2018; Wahlheim et al., 2021; Sinclair et al., 2020; Jang et al., 2018; Quent et al., 2021). Both signed (directional) and unsigned (magnitude) prediction errors have been shown to enhance memory, with effects mediated by dopaminergic and noradrenergic modulation of the hippocampus and related structures (Rouhani & Niv, 2021; Jang et al., 2019; Rouhani et al., 2023; Iordanova et al., 2021; Jang et al., 2018; Nasser et al., 2017).

3.3. Boundary Conditions and Moderators

The relationship between prediction error and memory is not always linear. Some studies report an inverted U-shaped or context-dependent effect, where intermediate levels of prediction error maximize memory, while very high or low levels may impair it (Nolden et al., 2025; Ortiz-Tudela et al., 2023; Pupillo et al., 2023; Liedtke et al., 2025; Decker et al., 2020; Ortiz-Tudela et al., 2021; Csink et al., 2021; Turan et al., 2024; Torrents-Rodas et al., 2023). The timing of prediction error relative to encoding, the type of memory (item vs. associative), and individual factors such as age and cognitive state also moderate these effects (Nolden et al., 2025; Shing et al., 2023; Ortiz-Tudela et al., 2023; Pupillo et al., 2023; Liedtke et al., 2025; Decker et al., 2020; Gruber & Fandakova, 2021; Ortiz-Tudela et al., 2021; Csink et al., 2021; Turan et al., 2024; Torrents-Rodas et al., 2023).

3.4. Real-World and Developmental Perspectives

Surprise and prediction error enhance memory not only in controlled experiments but also in real-world settings, such as autobiographical memory for surprising events (Antony et al., 2023; Antony et al., 2020; Antony et al., 2023). Developmental studies suggest that the effects of surprise on memory may change across the lifespan, with some evidence for reduced or even negative effects in children and older adults (Nolden et al., 2025; Shing et al., 2023; Gruber & Fandakova, 2021; Csink et al., 2021). The neural circuits underlying these effects continue to mature through adolescence (Gruber & Fandakova, 2021).

Key Papers

Paper	Methodology	Context/Population	Key Results
(Rouhani & Niv, 2021)	Behavioral modeling, fMRI	Adults	Both signed and unsigned reward prediction errors enhance learning and memory
(Sinclair et al., 2020)	fMRI, behavioral	Adults	Prediction errors disrupt hippocampal patterns, enabling memory updating
(Jang et al., 2019)	Behavioral, modeling	Adults	Positive reward prediction errors during decision making strengthen memory encoding
(Smout et al., 2019)	EEG, behavioral	Adults	Attention facilitates neural encoding of prediction errors, boosting selectivity for surprising stimuli
(Bein et al., 2021)	Behavioral	Adults	Mnemonic prediction errors promote detailed, distinct item memories

FIGURE 2 Comparison of key studies on surprise, prediction error, attention, and memory.

Top Contributors

Type	Name	Papers
Author	Nina Rouhani	(Rouhani & Niv, 2021; Rouhani et al., 2017; Rouhani et al., 2023)
Author	Y. Niv	(Rouhani & Niv, 2021; Rouhani et al., 2017; Rouhani et al., 2023)
Author	Alyssa H. Sinclair	(Sinclair & Barense, 2019; Sinclair et al., 2020; Sinclair & Barense, 2018; Sinclair et al., 2020)
Journal	*Neuroscience & Biobehavioral Reviews*	(Shing et al., 2023; Fernández et al., 2016; Nolden et al., 2024; Iordanova et al., 2021)
Journal	*Nature human behaviour*	(Jang et al., 2019; Antony et al., 2023)
Journal	*Learning & Memory*	(Sinclair & Barense, 2018; Bein et al., 2021)

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

4. Discussion

The evidence strongly supports the view that surprise and prediction error are central to the allocation of attention and the enhancement of memory encoding and updating (Rouhani & Niv, 2021; Sinclair et al., 2020; Jang et al., 2019; Smout et al., 2019; Sinclair & Barense, 2018; Shing et al., 2023; Holland & Schiffino, 2016; Rouhani et al., 2017; Frank et al., 2020; Bein et al., 2023; Antony et al., 2020; Brod et al., 2022; Greve et al., 2017; Wills et al., 2007; Rouhani et al., 2023; Bein et al., 2021; Kafkas & Montaldi, 2018; Brod, 2021; Wahlheim et al., 2021; Sinclair et al., 2020; Jang et al., 2018; Nasser et al., 2017; Quent et al., 2021). These effects are mediated by neuromodulatory systems (dopamine, noradrenaline) and involve dynamic changes in hippocampal and cortical representations (Sinclair et al., 2020; Jang et al., 2019; Smout et al., 2019; Rouhani et al., 2023; Iordanova et al., 2021; Nasser et al., 2017). However, the relationship is complex: the magnitude, timing, and context of prediction errors, as well as individual and developmental differences, can modulate whether surprise enhances or impairs memory and attention (Nolden et al., 2025; Ortiz-Tudela et al., 2023; Pupillo et al., 2023; Liedtke et al., 2025; Decker et al., 2020; Ortiz-Tudela et al., 2021; Csink et al., 2021; Turan et al., 2024; Torrents-Rodas et al., 2023).

Some studies highlight boundary conditions, such as the possibility of inverted U-shaped effects or the need for strong prior expectations to observe memory benefits from prediction errors (Ortiz-Tudela et al., 2023; Pupillo et al., 2023; Bein et al., 2021; Ortiz-Tudela et al., 2021; Quent et al., 2021). There is also evidence that surprise can sometimes impair memory, particularly in children or under high arousal (Nolden et al., 2025; Decker et al., 2020; Csink et al., 2021). The type of memory (item vs. associative, familiarity vs. recollection) and the explicitness of predictions also play a role (Ortiz-Tudela et al., 2023; Pupillo et al., 2023; Brod et al., 2022; Bein et al., 2021; Kafkas & Montaldi, 2018; Ortiz-Tudela et al., 2021; Turan et al., 2024; Quent et al., 2021).

Claims and Evidence Table

Claim	Evidence Strength	Reasoning	Papers
Surprise/prediction error enhances attention and memory encoding	Strong	Multiple converging studies show robust effects across paradigms and species	(Rouhani & Niv, 2021; Sinclair et al., 2020; Jang et al., 2019; Smout et al., 2019; Sinclair & Barense, 2018; Shing et al., 2023; Holland & Schiffino, 2016; Rouhani et al., 2017; Frank et al., 2020; Bein et al., 2023; Antony et al., 2020; Brod et al., 2022; Greve et al., 2017; Wills et al., 2007; Rouhani et al., 2023; Bein et al., 2021; Kafkas & Montaldi, 2018; Brod, 2021; Wahlheim et al., 2021; Sinclair et al., 2020; Jang et al., 2018; Nasser et al., 2017; Quent et al., 2021)
Dopaminergic and noradrenergic systems mediate these effects	Strong	Neuroimaging and pharmacological studies implicate these neuromodulators in prediction error-driven learning	(Rouhani & Niv, 2021; Jang et al., 2019; Smout et al., 2019; Rouhani et al., 2023; Iordanova et al., 2021; Jang et al., 2018; Nasser et al., 2017)
Boundary conditions: effect can be inverted U-shaped or context-dependent	Moderate	Some studies show maximal memory at intermediate prediction error, or context-specific effects	(Nolden et al., 2025; Ortiz-Tudela et al., 2023; Pupillo et al., 2023; Liedtke et al., 2025; Decker et al., 2020; Ortiz-Tudela et al., 2021; Csink et al., 2021; Turan et al., 2024; Torrents-Rodas et al., 2023; Quent et al., 2021)
Prediction error triggers memory updating and reconsolidation	Strong	Behavioral and neural evidence for memory labilization and updating after surprise	(Sinclair & Barense, 2019; Sinclair et al., 2020; Sinclair & Barense, 2018; Fernández et al., 2016; Nolden et al., 2024; Rouhani et al., 2017; Frank et al., 2020; Bein et al., 2023; Antony et al., 2020; Greve et al., 2017; Rouhani et al., 2023; Wahlheim et al., 2021; Sinclair et al., 2020)
Effects vary across development and individual differences	Moderate	Developmental and lifespan studies show heterogeneity in prediction error effects	(Nolden et al., 2025; Shing et al., 2023; Gruber & Fandakova, 2021; Csink et al., 2021)

Claim	Evidence Strength	Reasoning	Papers
In some cases, surprise can impair memory (e.g., high arousal, children)	Moderate	Some studies report negative or null effects, especially in specific populations or contexts	(Nolden et al., 2025; Decker et al., 2020; Ortiz-Tudela et al., 2021; Csink et al., 2021)

FIGURE Key claims and support evidence identified in these papers.

5. Conclusion

Surprise and prediction error are powerful drivers of attention and memory, enhancing the encoding and updating of information when expectations are violated. These effects are mediated by neuromodulatory systems and dynamic neural processes, but are subject to important boundary conditions and individual differences. Understanding these mechanisms has implications for education, clinical interventions, and real-world learning.

5.1. Research Gaps

Despite substantial progress, gaps remain in understanding the precise boundary conditions, developmental trajectories, and real-world applications of prediction error effects on attention and memory. More research is needed on the role of explicit vs. implicit predictions, the impact of different types of novelty, and interventions to harness these mechanisms in educational and clinical settings.

Research Gaps Matrix

Topic/Attribute	Adults	Children	Older Adults	Real-world Contexts	Neural Mechanisms
Prediction error & attention	15	4	3	5	10
Prediction error & memory encoding	18	5	4	6	12
Boundary conditions (U-shape, context)	8	2	1	2	5
Memory updating/reconsolidation	10	2	1	3	7
Explicit vs. implicit prediction	6	1	1	1	2

FIGURE Matrix of research topics and study attributes, highlighting areas with limited research coverage.

5.2. Open Research Questions

Future research should address the following questions to advance understanding and application of surprise and prediction error in attention and memory.

Question	Why
What are the precise neural mechanisms by which prediction error enhances memory encoding and updating?	Clarifying these mechanisms can inform interventions for learning and memory disorders.
How do developmental and individual differences modulate the effects of surprise on attention and memory?	Understanding variability can improve educational and clinical strategies across the lifespan.
What are the optimal conditions (magnitude, timing, context) for prediction error to enhance learning in real-world settings?	Identifying these can help design effective learning environments and interventions.

FIGURE Open research questions for future investigation on surprise, prediction error, attention, and memory.

In summary, surprise and prediction error are central to how attention is captured and memories are formed, but their effects depend on a complex interplay of neural, cognitive, and contextual factors.

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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