Metacognitive Regulation and Neurophysiological Mechanisms in Temporal Error Monitoring

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Abstract

Temporal error monitoring is a critical metacognitive ability, referring to the cognitive process by which individuals detect, evaluate, and adjust for potential biases during time perception. This paper systematically reviews the core task paradigms, metacognitive regulation mechanisms, and neurophysiological foundations in this field, with a focus on the roles of three mechanisms—self-assessment, feedback regulation, and decision confidence regulation—in modulating the accuracy of temporal judgments. Building upon this, and integrating neural activity evidence such as feedback-related negativity, β oscillations, and α oscillations, a "two-stage, three-pathway integration model" of temporal error monitoring is proposed to explain the synergistic effects between different mechanisms. Current research still faces limitations, such as the lack of a systematically elucidated neural mechanism, a dearth of developmental perspective studies, and insufficient ecological validity of paradigms. Future research could combine multimodal neuroimaging techniques with longitudinal developmental designs to explore more ecologically valid experimental paradigms, systematically reveal the dynamic coordination mechanisms across brain networks and their neural oscillation foundations, and apply relevant findings to the diagnosis of psychiatric disorders and cognitive interventions.

Full Text

Preamble

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摘要

Temporal error monitoring is a critical metacognitive ability, referring to the cognitive process by which individuals detect, evaluate, and adjust for potential biases during time perception. This paper systematically reviews the core task paradigms, metacognitive regulation mechanisms, and neurophysiological foundations of this field. It focuses on the roles of three specific mechanisms—self-assessment, feedback regulation, and decision confidence regulation—in modulating the accuracy of temporal judgments. Building upon these insights and incorporating neurophysiological evidence such as feedback-related negativity (FRN), β oscillations, and α oscillations, we propose a "Two-Stage, Three-Pathway Integrated Model" of temporal error monitoring to explain the synergistic interactions between these different mechanisms.

Current research in this field still faces several limitations, including an incomplete elucidation of neural mechanisms, a lack of developmental perspectives, and insufficient ecological validity in experimental paradigms. Future research should combine multimodal neuroimaging techniques with longitudinal developmental designs to explore more ecologically valid experimental paradigms. Such efforts will systematically reveal the dynamic coordination mechanisms across brain networks and their underlying neural oscillations, ultimately applying these findings to the diagnosis of psychiatric disorders and cognitive interventions.

关键词

Temporal Error Monitoring, Time Perception, Metacognition, and Neural Mechanisms

Introduction

Temporal error monitoring is a critical component of human cognitive control, allowing individuals to evaluate the accuracy of their own time-related behaviors and adjust future actions accordingly. This process is deeply intertwined with time perception—the subjective experience of duration—and metacognition, which refers to the higher-order ability to monitor and regulate one' s own cognitive processes. Understanding the neural mechanisms underlying how we detect and process timing errors is essential for unraveling the complexities of human performance in tasks ranging from simple motor coordination to complex decision-making.

Time Perception and Metacognitive Monitoring

Time perception is not a passive recording of physical time but an active construction by the brain. When individuals engage in timing tasks, such as estimating a specific duration or reproducing a rhythmic pattern, they often exhibit a degree of uncertainty. Metacognitive monitoring allows the brain to quantify this uncertainty, leading to a "feeling of error" when a performance deviates from the intended goal. Research suggests that this monitoring process relies on comparing an internal representation of the target duration with the actual perceived duration of the executed action.

Neural Mechanisms of Temporal Error Monitoring

The neural substrates of temporal error monitoring involve a distributed network of brain regions, primarily centered on the prefrontal cortex (PFC) and the anterior cingulate cortex (ACC). The ACC is widely recognized as a hub for performance monitoring, generating signals such as the Error-Related Negativity (ERN) when a mismatch between intended and actual outcomes is detected. In the context of timing, the supplementary motor area (SMA) and the basal ganglia also play pivotal roles, as they are fundamental to both the generation of temporal intervals and the internal representation of time.

Electrophysiological studies have identified specific neural markers associated with temporal metacognition. For instance, the amplitude of certain event-related potentials (ERPs) correlates with the magnitude of timing errors, suggesting that the brain maintains a continuous scale of performance accuracy rather than a simple binary (correct/incorrect) classification. Furthermore, oscillations in the theta and beta frequency bands have been implicated in the communication between the ACC and motor areas during the correction of timing deviations.

The Role of Feedback and Learning

Temporal error monitoring is highly adaptive. When external feedback is provided, the brain integrates this objective information with internal metacognitive estimates to update internal models of time. This process of reinforcement learning is mediated by dopaminergic signaling within the striatum, which

1 引言

In the complex environments of daily life, individuals must navigate variations across multiple tasks that often rely on the accurate perception of time. For example, in competitive sports, athletes must precisely control the rhythm of every movement to perform at their peak. During flight, pilots must monitor and adjust their timing estimates at every critical juncture to ensure precise timing for approach and landing, thereby avoiding potential safety risks. However, the accuracy of time perception is frequently susceptible to interference from factors such as emotional states, attention levels, and task characteristics, leading to biases between subjective temporal judgments and objective time [?, ?, ?]. Faced with such uncertainty, humans have developed a critical metacognitive ability: temporal error monitoring (TEM). This ability enables individuals to detect and correct errors in their time estimations without external feedback, thereby improving the accuracy of temporal perception [?, ?].

Temporal error monitoring is unique compared to other types of metric error monitoring, such as spatial or numerical error monitoring. First, the unidirectional flow of time dictates that temporal error monitoring must be real-time and instantaneous. Individuals must make judgments within extremely short time windows, such as performing a real-time comparison between a reproduced duration and a target duration [?, ?, ?]. This transience differs from the repeatable and verifiable static judgments in spatial error monitoring, where verification and adjustment can occur through retrospective correction. Second, errors in temporal tasks typically accumulate incrementally; individuals must not only monitor single judgments but also continuously adjust and correct time estimation errors throughout the entire task process. Therefore, temporal error monitoring is not merely the detection of a single error but a continuous, dynamic adjustment process that requires individuals to constantly update their perception of time as it passes. Empirical research has found that temporal error monitoring possesses a "temporal foreknowledge" characteristic, meaning it can read out potential temporal error signals in real-time before the behavioral output, thereby enabling within-trial self-correction [?, ?]. This feature distinguishes it from traditional post-hoc error monitoring mechanisms. Furthermore, the confidence assessment process in temporal error monitoring is highly subjective and complex. An individual' s time estimation is easily influenced by internal rhythms, emotional states, attentional resources, and cognitive load.

These factors render the evaluation process more uncertain. Additionally, unlike spatial or numerical judgments that can rely on external references, temporal error monitoring primarily depends on the brain's internal timing system, which adds extra cognitive challenges. These characteristics of temporal error monitoring present unique challenges in the detection, evaluation, and adjustment of time estimation, further highlighting its importance as a metacognitive monitoring process in the study of time perception.

Temporal error monitoring is essentially a manifestation of metacognitive ability [?, ?]. Metacognition includes both the awareness and evaluation of cognitive processes (metacognitive monitoring) and the active adjustments made based on those evaluation results (metacognitive regulation) [?, ?]. In time estimation tasks, individuals need to both detect their judgment biases in real-time and adjust their attentional allocation or calibrate their internal temporal representations accordingly [?, ?]. Consequently, temporal error monitoring integrates the two levels of monitoring and regulation to collectively enhance the accuracy and adaptability of temporal judgments.

Although research on temporal error monitoring has yielded significant results, its core functional mechanisms and influencing factors have yet to be systematically revealed. Current research focuses primarily on how individuals perceive and reflect on temporal biases, while a unified framework for the metacognitive regulatory mechanisms and neurophysiological pathways underlying this process is still lacking. Specifically, how do individuals dynamically integrate various types of regulatory information—such as self-assessment, external feedback, and decision confidence—across different tasks and contexts to monitor and correct time estimation errors?

Furthermore, how do these regulatory processes influence the accuracy of time perception and behavioral adjustment through the coordination of specific neural networks? This paper focuses on temporal error monitoring within the range of seconds—the core window where existing behavioral and neurophysiological research is most concentrated—and proposes the following core scientific questions: In temporal error monitoring, how do metacognitive regulatory mechanisms act upon an individual’ s time estimation and behavioral adjustment? How are the neurophysiological foundations of these mechanisms integrated into a preliminary theoretical framework? Centered on these questions, this paper systematically reviews existing research paradigms and combines cognitive models, computational models, and neurophysiological evidence to explore the mechanisms of temporal error monitoring, subsequently proposing potential directions and theoretical hypotheses for future research.

2.1 选择退出范式

The Opt-Out Task indirectly reflects a participant’ s ability to monitor their own timing errors by allowing them to abandon or withdraw from a trial during a time estimation task. In this paradigm, after completing a time reproduction task, participants decide whether to keep or discard (opt out of) their current result based on a subjective judgment of their estimation accuracy, with the goal of optimizing their total task score (Yallak & Balcı, 2022).

The primary advantage of this paradigm is its ability to directly reflect an individual’ s real-time sensitivity to temporal errors through autonomous withdrawal behavior in the absence of external feedback. Furthermore, variations in opt-out behavior across different trials facilitate an assessment of the stability of the monitoring process. However, this paradigm is susceptible to individual risk preferences, which may lead to an overestimation of actual monitoring capabilities.

2.2 自我评估范式

The self-evaluation task requires participants to reassess the accuracy of their own judgments after completing a time estimation, such as by directly judging the magnitude and direction of their errors [?, ?, ?, ?, ?, ?, ?, ?] or by comparing the relative accuracy of different estimates [?, ?]. This paradigm directly examines the metacognitive ability to evaluate timing errors through an individual’ s assessment of their own estimation accuracy, the magnitude and direction of bias (e.g., “too long”or “too short”judgments), and their level of confidence. This paradigm possesses high ecological validity, as it effectively simulates the process by which individuals monitor timing errors and adjust timing strategies in real-world scenarios. It is particularly suitable for exploring the dynamic adjustment of timing strategies, making it a representative paradigm for investigating the metacognitive regulatory mechanisms of timing error monitoring. However, because participants' evaluations rely primarily on subjective judgment processes, they may be influenced by factors such as emotion or task difficulty, which can subsequently affect the objectivity of the results.

Consequently, when employing the self-evaluation paradigm, researchers often need to integrate other objective indicators—such as actual error values, reaction times, eye-tracking data, or neurophysiological measures—into a comprehensive analysis to enhance the reliability of their conclusions.

2.3 重试决策范式

The retry-decision paradigm examines an individual' s ability to regulate behavior following a temporal error by utilizing feedback information. This paradigm typically employs a two-stage design: participants first complete a duration reproduction task and subsequently decide whether to opt for a "retry" based on the provided feedback [**?**, **?**]. This design transforms external feedback into a signal that drives behavioral adjustment, using the retry choice as a quantifiable metric to reflect the individual' s capacity to modify subsequent actions in response to error information. Compared to the previous two paradigms, the retry-decision paradigm helps distinguish the computation of prediction errors from the subsequent process of strategic adjustment; furthermore, the retry rate provides a direct reflection of an individual' s behavioral flexibility. However, if the feedback information is too explicit, it may induce strategic responding, causing participants to rely more on external feedback than on internal monitoring. This can compromise the accurate assessment of an individual' s spontaneous monitoring capabilities. Therefore, experimental designs must carefully control the clarity of feedback to prevent external information from over-interfering with participant behavior.

These three task paradigms each have a distinct focus, revealing key processes of temporal error monitoring from different perspectives and collectively expanding our understanding of its underlying cognitive mechanisms. Specifically, the opt-out paradigm reveals an individual' s implicit awareness and self-regulatory capacity regarding their own temporal errors by requiring them to autonomously decide whether to retain a response result in the absence of external feedback. In contrast, the self-evaluation paradigm focuses on investigating the individual' s explicit awareness and subjective judgment of their own time perception

biases, while the retry-decision paradigm focuses on behavior regulation driven by feedback. These three categories of paradigms reveal the monitoring, evaluation, and correction processes of temporal error monitoring from diverse angles, providing a variety of experimental tools for subsequent mechanistic research. Future studies could further integrate these multiple paradigms to enhance the ecological validity and dynamism of experiments, thereby more comprehensively uncovering the process mechanisms and neural foundations of temporal error monitoring.

3 时间错误监控中的元认知调节机制

Temporal error monitoring is generally considered a metacognitive process; however, it is not implemented through a single mechanism but rather relies on multiple complementary regulatory pathways. Based on the source of information and the level of operation, these can be categorized into three mechanisms: self-assessment, feedback regulation, and decision confidence. These mechanisms influence how individuals correct temporal estimation biases across different levels of processing.

3.1 自我评估机制

In the absence of external feedback, temporal error monitoring relies primarily on self-assessment mechanisms. This mechanism enables individuals to dynamically correct their temporal estimates by leveraging internal representations and metacognitive monitoring. Bader and Wiener (2021) found that in performance without feedback, the central tendency effect—also known as the Vierordt effect, characterized by the overestimation of short intervals and underestimation of long intervals—gradually diminishes, demonstrating an independent capacity for temporal error detection and regulation. Furthermore, existing research indicates that individuals can report the direction and magnitude of their own temporal errors at the single-trial level, providing direct evidence for self-monitoring in the absence of external feedback (Öztel et al., 2021; Kononowicz & van Wassenhove, 2019). From the perspective of motor execution, research by Bilgin and Kononowicz (2025) further suggests that participants can judge their own temporal estimation biases even in contexts with high motor interference, reflecting a self-assessment capability based on internal clock representations.

The Sequential Diffusion Process proposed by Akdoğan and Balcı (2017) provides a theoretical framework for understanding this mechanism. Based on the Opposing Poisson Drift-Diffusion Model (OPDDM) (Simen et al., 2011), this framework posits that temporal estimation arises from the noisy accumulation and threshold competition of multiple neural integrators. When a specific integrator reaches the threshold first, it triggers a corresponding response; thus, each estimate exhibits a degree of stochastic variability. Furthermore, after the response occurs, the system compares the differences in triggering times among different integrators to determine whether the estimate was “too early” or “too late” and to quantify the magnitude of the error. According to this model, the signal source for self-assessment is not a single “internal clock” but rather the result of comparison and competition between the outputs of multiple integrators. This distributed signal comparison provides individuals with intrinsic error information, allowing them to achieve incremental calibration and adjustment of temporal estimates through internal monitoring, even in the absence of external feedback.

In addition to relying on internal self-assessment processes to monitor and correct temporal errors, temporal estimation can also be regulated through external feedback signals. The feedback regulation mechanism is a class of regulatory processes based on external feedback information used to calibrate and adjust the temporal estimation process.

3.2 反馈调节机制

The feedback regulation mechanism refers to the process by which individuals rely on external feedback information to correct and optimize their performance during temporal error monitoring [?, ?]. By providing an objective reference, feedback effectively compensates for the biases and uncertainties inherent in the internal sensory system. Based on the dimensions of information provided, feedback can be categorized into three types: correctness feedback, absolute error feedback, and signed error feedback. Correctness feedback provides a binary judgment on whether a response falls within a target interval (e.g., "Correct/Incorrect"); absolute error feedback quantifies the magnitude of the error without specifying its direction (e.g., "Estimation error of 300 ms"); and signed error feedback provides both the direction and magnitude of the error (e.g., "Underestimated by 300 ms"), thereby enhancing the specificity of the correction [?, ?, ?].

Significant differences exist in how different types of feedback influence temporal error monitoring. Research by Riemer et al. [?] demonstrated that providing trial-by-trial feedback containing both error direction and magnitude in time reproduction tasks significantly reduces mean error and improves an individual' s monitoring performance regarding the direction of deviation.

Compared to providing only absolute error feedback, signed error feedback is more advantageous in reducing temporal underestimation. This is because signed error feedback provides dual calibration information— "error polarity" and "relative magnitude" —enabling more efficient adjustments. Experimental results from Bader and Wiener [?] also show that participants receiving feedback achieved more precise time estimations in subsequent trials, with a significant decrease in the coefficient of variation. However, early research also pointed out that feedback struggles to completely eliminate systematic bias [?, ?], suggesting that its optimization effects have boundaries.

Beyond direct improvements in precision and variability, feedback regulation is closely related to an individual' s self-assessment mechanism. Chung et al. [?] found that when feedback is consistent with an individual' s self-assessment, participants are more likely to modify their behavior based on that feedback; conversely, when the two are inconsistent, individuals often rely on their own judgment rather than external information. Related studies also suggest that the role of feedback is not a unidirectional input but rather a complementary system with the self-assessment mechanism, together maintaining the stability and flexibility of time estimation [?, ?]. Research by Li et al. [?] indicates that in temporal tasks, feedback primarily influences the decision-making and behavioral output stages rather than the early encoding or memory stages. In contrast, in spatial perception tasks, the role of feedback is not limited to late-stage decision-making or behavioral output; it may instead alter the information variables utilized by the perceiver and recalibrate spatial scale representations [?, ?, ?]. This suggests that feedback mechanisms in different types of tasks may differ in their timing of action:

Temporal tasks primarily affect the decision stage, whereas spatial tasks may involve representational adjustments at an earlier perceptual stage. Furthermore, different feedback modalities lead to differentiated effects, and the robustness of these mechanistic differences requires further systematic comparative research across tasks. In summary, while feedback can improve the precision of time estimation, its effect is limited and should be viewed as a supplement to internal mechanisms rather than a primary reliance. Over-reliance on feedback may weaken an individual' s intrinsic regulatory capacity, leading to performance declines in the absence of external references. Additionally, the effective utilization of feedback is closely related to an individual' s subjective confidence level, an issue we will explore in detail within the section on decision confidence regulation mechanisms.

3.3 决策信心调节机制

The decision confidence regulation mechanism reflects an individual's assessment of the reliability of their own judgments during temporal tasks and serves as a basis for behavioral adjustment. Confidence judgment is not merely a reflective evaluation of performance; rather, it is a calibration process of decision accuracy –specifically, the consistency between confidence ratings and actual performance accuracy (Lichtenstein et al., 1977). Research indicates that more accurate confidence calibration is associated with higher levels of error monitoring (Lei et al., 2020). In time processing tasks, Akdoğan and Balcı (2017) found that as temporal estimation bias increases, participants' confidence levels significantly decrease. Furthermore, participants were able to accurately judge the direction of their temporal errors, suggesting that confidence regulation plays a vital role in the monitoring process.

Yallak and Balcı (2022) employed the opt-out paradigm as an implicit assessment of confidence regulation and found that participants were more likely to retain their results in trials with smaller errors.

This suggests that individuals are capable of self-screening timing results based on their confidence levels. Recent studies have expanded the understanding of confidence regulation mechanisms across multiple dimensions. Balcı and Öztel (2026) proposed that confidence signals can be generated in real-time before a behavior occurs and improve precision by adjusting timing thresholds. This indicates that confidence regulation is not merely a post-hoc reflection but possesses prospective metacognitive functions. Similarly, Charles and Yeung (2019) utilized perceptual judgment tasks to demonstrate that individuals continue to sample evidence after making an initial choice. This subsequent evidence influences both confidence judgments and error detection, suggesting that the two may share a dynamic evidence accumulation mechanism.

Simultaneously, confidence is driven not only by direct temporal perception but also by external task characteristics. For instance, when task complexity increases, individuals tend to overestimate their reaction times; this bias stems more from inferences about task difficulty than from objective performance itself (Pavailler et al., 2025). Further research indicates that subjective temporal experience can itself influence metacognitive evaluation: Isham (2020) found that manipulating a participant' s perceived decision time can systematically alter their judgment of task difficulty. These results suggest that the confidence regulation mechanism is a dynamic process of multi-source information integration. Furthermore, a review by Yeung and Summerfield (2012) pointed out that confidence and error monitoring may rely on similar post-decisional processing mechanisms at both computational and neural levels. This perspective provides a broader theoretical framework for understanding the role of confidence regulation in temporal error monitoring.

In summary, self-assessment mechanisms play a fundamental role in the process of temporal error monitoring, as they are responsible for the detection and preliminary correction of temporal errors, helping individuals revise internal temporal representations in the absence of external feedback. Feedback regulation mechanisms intervene once external information becomes available, utilizing feedback signals to correct temporal estimation biases and thereby improving judgmental accuracy and strategic flexibility. In contrast, the confidence regulation mechanism does not directly produce error signals but instead operates at a higher functional level. When task difficulty increases, feedback information becomes ambiguous, or strategic conflicts arise, it coordinates and balances self-assessment and feedback regulation by adjusting subjective confidence levels. These three mechanisms are not independent; rather, they interact and complement one another within specific tasks. Self-assessment establishes the foundation for monitoring, feedback regulation further enhances the precision of corrections when external cues are available, and confidence regulation maintains the stability and flexibility of the overall system by balancing self-assessment and feedback regulation in contexts of high uncertainty. It is precisely this division of labor and collaboration that enables individuals to achieve efficient and flexible regulation within complex and variable temporal judgment environments.

4 时间错误监控的神经生理机制

To further understand the neural implementation mechanisms of temporal error monitoring, this paper synthesizes existing research across three dimensions: self-assessment, feedback regulation, and decision confidence.

4.1 自我评估机制的神经生理基础

Some researchers argue that the implementation of self-evaluation depends on whether the brain possesses internal temporal representations that can be read by the individual. In recent years, a wealth of neurophysiological evidence has provided strong support for this view, revealing the critical role of specific neural oscillatory activities and their underlying functional networks in the self-evaluation of temporal error monitoring. At the level of oscillatory mechanisms, studies have demonstrated that β-band activity plays a key role in interval production. Kononowicz and van Rijn (2015) found that in a 2.5-second interval production task, enhanced β-band (15–40 Hz) oscillatory power was associated with longer subjective time estimates, and that β activity at the onset of interval production could predict the length of the interval subsequently generated by the individual.

This suggests that β waves play an important role in the internal prediction and error monitoring of temporal representations. Subsequent research has further indicated that β power is not only positively correlated with the length of the generated interval but is also closely related to its accuracy (Kononowicz, Roger, & van Wassenhove, 2019). Source localization results show that this β activity primarily originates from the Timing Network (TN), including the Supplementary Motor Area (SMA) and the Pre-Supplementary Motor Area (Pre-SMA), suggesting that these regions may play a pivotal role in the formation of temporal representations. In addition to correlational evidence, Wiener et al. (2018) applied 20 Hz transcranial alternating current stimulation (tACS) to the mid-frontal region and found a systematic shift in individuals' time estimation standards, manifesting as a tendency to produce longer intervals.

This causal evidence suggests that β waves not only reflect internal signals but are also directly involved in the encoding and maintenance of temporal memory standards. Furthermore, a magnetoencephalography (MEG) study by de Lange et al. (2013) revealed that pre-stimulus β activity in the motor cortex reflects an individual's perceptual expectations and shifts the decision starting point before evidence accumulation begins. This suggests that β waves may influence subsequent judgments by modulating internal benchmarks or starting points. Taken together, these results indicate that β waves serve as both predictive signals for temporal representation and important neural cues for error monitoring.

In addition to β waves, the activity characteristics of α waves (8–14 Hz) have also been proven to be closely related to the self-evaluation process. Specifically, during the initial stage following the completion of interval production, α power shows a significant negative correlation with an individual' s subjective evaluation: the more accurate the evaluation, the lower the α power (Kononowicz & van Wassenhove, 2019). This decrease in power is thought to reflect the individual' s active "reading" of the temporal state previously encoded by β waves, representing the neural implementation mechanism of internal error inference. Further source localization analysis indicates that this α activity primarily originates from regions such as the precuneus and the medial prefrontal cortex (Kononowicz & van Wassenhove, 2019), which is highly consistent with previous research on self-monitoring and conscious awareness. These findings suggest that α waves primarily serve the functions of error reading and reflection during self-evaluation.

Beyond single frequency bands, interactions between different oscillatory bands and large-scale functional connectivity between brain regions have also proven essential to the self-evaluation mechanism of temporal error monitoring. Research has found that cross-frequency coupling between α and β waves can predict the precision of an individual' s time estimation (Grabot et al., 2019), suggesting that the interaction of oscillations across different bands may provide a more stable internal signal for subsequent self-evaluation. fMRI studies have further revealed the brain network foundations of the self-evaluation mechanism in temporal error monitoring. Bader and Wiener (2024) found that cross-network functional connectivity between the Default Mode Network (DMN) and the TN is significantly enhanced during the estimation phase of initial trials, indicating that their collaboration facilitates the formation of internal temporal representations and the detection of potential errors. Within this framework, the DMN (including the superior frontal gyrus, precuneus, and posterior cingulate cortex) integrates subjective time perception with error reflection through metacognitive monitoring to participate in the self-evaluation of temporal errors; meanwhile, the TN (centered on the SMA and encompassing the precentral gyrus and right supramarginal gyrus) is primarily responsible for the generation and adjustment of temporal actions. Even in the absence of directional feedback, this internal mechanism can support behavioral adjustments to some extent, though its regulatory efficiency remains relatively limited. Thus, self-evaluation does not rely on a single brain region or frequency band but is supported by multi-band oscillations and cross-network collaboration.

In summary, self-evaluation is not a single process but a complex system that relies on the coordination of β and α oscillations, as well as the DMN and TN networks. β waves may be responsible for temporal prediction, while α waves participate in error reading; together, they achieve the generation and subsequent evaluation of temporal representations.

This mechanism reveals the dynamic and systemic nature of self-evaluation and lays the foundation for understanding the mechanisms of feedback regulation and confidence modulation.

4.2 反馈调节机制的神经生理基础

In contrast, when external feedback is available, the brain further reorganizes its networks based on existing self-assessment mechanisms. Research by Bader and Wiener (2024) demonstrates that across repeated trials, the activation range of the Default Mode Network (DMN) expands significantly and forms a more concentrated collaboration with the local activity of the Task Network (TN), particularly the Supplementary Motor Area (SMA). This suggests that network reorganization driven by external feedback can enhance the accuracy of temporal reproduction. It is important to emphasize that while the DMN participates in error monitoring even in the absence of feedback, external feedback further strengthens its monitoring and regulatory functions, allowing it to play a greater role on the basis of self-assessment. Meanwhile, the SMA is responsible for executing specific corrective actions; the dynamic interaction between these two regions provides the neurological foundation for feedback regulation.

ERP studies have revealed the phased characteristics of feedback regulation mechanisms. Feedback-Related Negativity (FRN) typically appears within 200-300 ms after feedback presentation and is particularly sensitive to negative feedback, reflecting the individual' s rapid detection of prediction error signals.

Chung et al. (2024) found that an increase in FRN amplitude not only signifies heightened sensitivity to negative feedback but also predicts an individual' s awareness of their own performance bias and subsequent corrections. More importantly, the amplitude of the FRN is related to whether the individual has formed an internal prediction of their own interval reproduction performance.

When FRN amplitude is larger, individuals tend to make decisions based on their own performance rather than the feedback itself, suggesting that the FRN acts as a bridge in the integration of "internal error monitoring" and "external feedback." In contrast, the P3 component typically appears 300-600 ms after feedback and is more sensitive to positive feedback. The amplitude of the P3 reflects the processing of feedback value and motivational significance; its enhancement indicates an individual' s positive evaluation of the feedback' s value, as well as the motivation to maintain task engagement and behavioral persistence driven by positive feedback. Existing research indicates that P3 amplitude is influenced not only by emotional valence but also by the relevance of the feedback to task goals [**?**, **?**, **?**], further supporting its role in feedback-driven motivational regulation. Overall, the functions of the FRN and P3 in temporal error monitoring are complementary: the former biases toward error detection and signal correction, while the latter reflects more motivation-driven and sustained regulation.

In addition to the FRN and P3 components, recent research has provided evidence for other indicators. Li et al. (2023) found that in a standard time perception task, feedback primarily regulated the Contingent Negative Variation (CNV) component during the decision-making stage, thereby reducing systematic bias in time estimation. This study points out that the effect of feedback is more evident in the behavioral output stage, manifesting as the regulation of response preparation and judgment strategies.

rather than altering early temporal representations. This result provides a new perspective for understanding the regulatory role of feedback in timing tasks.

4.3 决策信心调节机制的神经生理基础

Existing research has demonstrated that decision confidence can be represented across different levels of neural activity. Human fMRI studies have found that activity in the medial prefrontal cortex, particularly the perigenual anterior cingulate cortex (pgACC), is closely correlated with decision confidence. Furthermore, single-neuron recording studies have indicated the presence of neuronal responses related to decision confidence within the human medial temporal lobe [**?**, **?**, **?**]. These findings provide robust evidence that confidence possesses measurable neural representations.

Subsequent modeling research has proposed that specialized "confidence neurons"may exist in the brain. These neurons are hypothesized to form an estimate of the probability of a correct decision by monitoring the rate of neural activity associated with evidence accumulation. Although this model was initially developed within a general decision-making framework, recent reviews in the field of temporal cognition have suggested it as a potential mechanism for explaining temporal error monitoring. However, this theoretical model still lacks direct empirical validation within the context of temporal cognitive tasks [**?**, **?**, **?**].

Lak et al. (2014) utilized a "waiting time" based confidence wagering task to demonstrate the critical role of the rat orbitofrontal cortex (OFC) in confidence reporting. Their experiments revealed that even after temporary inactivation of the OFC, the rats' perceptual judgments and average waiting times remained unaffected; however, their waiting times no longer reliably reflected decision confidence. This finding suggests that the OFC plays a central role in second-order monitoring and confidence modulation. These results indicate that even when first-order perception or temporal judgments remain intact, impairment of second-order confidence modulation mechanisms can significantly alter how error information is utilized at the behavioral level.

Similar trends have been observed in human research. Doenyas et al. (2019) found in a behavioral study that individuals with Autism Spectrum Disorder (ASD) showed no significant differences from control groups in first-order tasks, such as perceptual judgment and time reproduction. However, the correlation between their subjective confidence and actual error was significantly weakened, reflecting a deficit in second-order error monitoring and confidence modulation capabilities. Although that study did not record neural activity, the authors speculated in their discussion that this impairment in metacognitive function may be associated with dysfunction in the medial prefrontal cortex.

These behavioral results suggest that the prefrontal cortex may play a critical role in temporal error monitoring, providing a valuable foundation for subsequent neuroimaging research. In summary, ERP components and neural oscillations reveal the neurophysiological basis of the three metacognitive regulatory mechanisms from distinct perspectives. These findings also provide an important reference for the development of subsequent integrated models.

5 A New Integrative Framework: The Two-Stage, Three-Pathway Model of Temporal Error Monitoring

Despite the accumulation of substantial evidence regarding task paradigms, key brain regions, and neural processes, existing findings remain fragmented across various theoretical contexts. There is still a lack of a unified explanatory framework to describe how temporal errors are generated, how they are evaluated, and how they subsequently influence behavioral adjustment.

Based on the synthesis of existing research, we propose a "Two-Stage, Three-Pathway Model" for temporal error monitoring. This framework aims to integrate the cognitive and neural mechanisms underlying the detection and processing of timing inaccuracies.

5.1 The Two-Stage Processing Architecture

The model posits that temporal error monitoring unfolds across two distinct stages: the **Error Evaluation Stage** and the **Behavioral Adjustment Stage**.

In the first stage, the system identifies discrepancies between the intended temporal goal and the actual temporal outcome. This involves the integration of sensory feedback with internal timing representations. In the second stage, the evaluated error information is utilized to update internal models and modify subsequent motor commands, ensuring that future timing behavior aligns more closely with the target.

5.2 The Three Pathways of Error Processing

To account for the diversity of temporal tasks and the complexity of neural implementation, we propose three specific pathways within this framework:

1. **The Sensory-Motor Feedback Pathway**: This pathway primarily handles immediate, low-level discrepancies between motor output and sensory input. It relies on rapid feedback loops to maintain real-time synchronization.
2. **The Cognitive-Comparison Pathway**: This pathway involves higher-order cognitive processes where the perceived duration is compared against a stored reference memory. It is critical for interval timing and tasks requiring explicit temporal judgments.
3. **The Predictive-Update Pathway**: This pathway focuses on the proactive adjustment of internal timing templates. By utilizing error signals from previous trials, it facilitates long-term learning and the optimization of temporal strategies.

By integrating these stages and pathways, the proposed model provides a comprehensive structure for understanding the dynamic nature of temporal error monitoring and its role in adaptive human behavior.

Based on this, the present study proposes a two-stage, three-pathway model for timing error monitoring (see [Figure 1: see original paper]). This model aims to provide a comprehensive framework by integrating the generation, evaluation, and adjustment processes of timing errors.

1. The Two-Stage, Three-Pathway Model of Timing Error Monitoring

The proposed model conceptualizes timing error monitoring as a dynamic process divided into two primary stages: the error detection stage and the subsequent adjustment stage. Within these stages, three distinct pathways facilitate the processing of temporal information and the correction of performance.

1.1 The Generation and Detection of Timing Errors

In the first stage, the model accounts for how timing errors are generated and subsequently detected by the internal monitoring system. This involves comparing the actual temporal output with the intended target duration. When a discrepancy arises between the internal representation of time and the motor execution, an error signal is triggered. This detection mechanism is crucial for maintaining accuracy in tasks requiring precise temporal control, such as rhythmic tapping or speech production.

1.2 The Three Pathways of Error Processing

The model identifies three specific pathways that handle the flow of information during the monitoring process:

1. **The Feedforward Pathway:** This pathway utilizes internal models to predict the sensory consequences of a timed action before it is fully executed. By comparing predicted feedback with the intended goal, the system can preemptively identify potential errors.
2. **The Feedback Pathway:** This pathway relies on actual sensory input (e.g., auditory or tactile feedback) to evaluate performance. It provides the necessary data to confirm whether the executed timing matched the desired parameters.
3. **The Evaluative Pathway:** This pathway integrates information from both feedforward and feedback sources to determine the magnitude and direction of the timing error. It serves as the basis for high-level cognitive appraisal and the initiation of corrective strategies.

1.3 The Adjustment Stage

Once an error is detected and evaluated, the model enters the second stage: adjustment. During this phase, the system utilizes the error information to modify subsequent temporal behavior. These adjustments can occur on a trial-by-trial basis, leading to short-term corrections, or contribute to long-term motor learning and the refinement of internal temporal representations. By closing the loop between execution and monitoring, the two-stage, three-pathway model explains how humans achieve and maintain high levels of temporal precision in complex environments.

The regulatory process provides a structurally clear and hypothesis-generating theoretical framework for testing relevant mechanisms.

Note: In the figure, the first stage is based on Scalar Expectancy Theory to form an error representation that includes both bias and uncertainty. The second stage corresponds to the metacognitive evaluation and regulation process developed from this representation. Within this stage, the self-evaluation path and the feedback regulation path provide endogenous and exogenous bias information, respectively. Meanwhile, the confidence regulation path adjusts the parameters of the subsequent integration process based on uncertainty cues. In the figure, $\hat{e}_{int}$ represents···

$\hat{e}_{int}$ represents the endogenous bias estimation formed based on internal error representations; $\hat{e}_{ext}$ represents the exogenous bias estimation formed based on historical feedback information; C represents the individual' s subjective confidence in the reliability of the current temporal judgment result.

w, α, and θ represent the information integration weight, the feedback learning rate, and the decision threshold, respectively. Solid arrows denote substantive input or processing flows, while dashed arrows indicate parameter adjustment or update relationships. External feedback from the current trial (if provided) is updated across trials to form historical feedback information, which then enters the feedback regulation path in subsequent trials.

This model divides temporal error monitoring into two interconnected yet functionally distinct stages. The first stage is the temporal encoding and error representation generation phase, which is primarily responsible for forming internal temporal error representations. The second stage is the metacognitive evaluation and regulation phase, which focuses on monitoring, integrating, and utilizing the error representations formed in the previous stage. This division is established because the generation of a temporal error is not equivalent to the subsequent processing based on that outcome: the former produces a primary error representation, while the latter involves second-order evaluation and regulation built upon that foundation. Metacognitive research indicates that after forming a primary judgment, individuals utilize various cues to monitor that judgment. This process typically does not directly change the initial···

Metacognitive monitoring is not merely a primary judgment itself, but rather functions as a second-order evaluation built upon primary judgments. It further influences strategy selection, resource allocation, and subsequent control processes [**?**, **?**, **?**, **?**].

In the first stage, the model utilizes Scalar Expectancy Theory (SET) as its computational foundation to explain how temporal information is transformed into internal representations of temporal error through clock encoding, memory representation, and comparison processes [**?**]. It is important to note that the output of this stage is not a single, discrete temporal judgment, but rather an internal representation containing two distinct types of information. The first is the content of the error, which includes the direction and magnitude of the bias. The second is the qualitative information accompanying this representation, such as its stability, precision, or cues regarding its uncertainty. While the former represents "how much and in what direction" the timing deviated, the latter reflects "how reliable this representation is." Consequently, the first stage generates the temporal error itself while simultaneously providing the necessary informational basis for subsequent metacognitive processing.

In the second stage, the model further distinguishes between three interrelated but qualitatively different processing pathways. The first of these is the self-evaluation pathway. This···

The first path primarily relies on the content information within the internal temporal error representation to evaluate the direction and magnitude of the current judgment bias. This process generates endogenous bias information $\hat{e}_{int}$, providing a substantive basis for subsequent integration [**?**, **?**, **?**]. The second path is the anti-

···feedback regulation pathway. This pathway relies on external feedback information accumulated from previous trials to perform external calibration of the current judgment, thereby generating exogenous bias information $\hat{e}_{fb}$. Its operation is predicated on the availability of prior feedback; rather than simply utilizing feedback from the current trial, it depends on the cumulative information formed across multiple trials.

The third pathway is the confidence regulation pathway. Unlike the first two pathways, this route does not directly provide new bias content. Instead, it evaluates the reliability of the current temporal judgment based on uncertainty cues accompanying the error representation, thereby forming subjective confidence C. Here, uncertainty cues primarily refer to the stability, precision, or credibility of the error representation, rather than the direction or magnitude of the error itself. These cues may originate from the variability of internal representations, as well as experiential and state-based cues such as processing fluency, attention levels, degree of hesitation, and reaction times; furthermore, they may be calibrated by historical feedback. The primary role of this pathway is not to rewrite the error content, but rather to influence how different information sources function in subsequent decision integration by modulating parameters such as integration weights (w), learning rates (α), and judgment thresholds (θ) [**?**, **?**, **?**].

This conceptual framework is further supported by research on feedback processing and learning updates. Existing studies demonstrate that subjective confidence is not merely an incidental experience accompanying a judgment;

rather, it actively influences how feedback information is processed within the current trial and how it facilitates updates across subsequent trials. Frömer et al. (2021) found that the neural representation of feedback reflects more than just objective error; it integrates internal expectations formed by the individual based on their own performance alongside subjective confidence. Specifically, the feedback-related negativity (FRN) is sensitive to the degree of deviation between feedback and internal expectations. In contrast, the subsequent P3 component further integrates prediction errors with subjective confidence and correlates with the magnitude of learning updates across trials.

Similarly, research from general learning tasks indicates that the feedback-related P300 component reflects the subjective importance or update weight of feedback information, with its amplitude being modulated by levels of subjective confidence [**?**, **?**]. Furthermore, as a subjective readout of judgment reliability, confidence influences the weighting of new feedback during belief updating; conversely, feedback and error information continuously contribute to the calibration of judgment reliability across trials [**?**, **?**, **?**]. Collectively, these lines of evidence support the fundamental hypothesis of the present model: the confidence modulation pathway does not directly rewrite error content, but instead operates through a parameter adjustment mechanism that acts upon subsequent decision integration and behavioral regulation.

It should be emphasized that the second stage is not a passive reading of the output from the first stage. Instead, through the synergistic action of three distinct pathways, the system integrates the initial results with contextual information to achieve a more robust synthesis.

Endogenous bias information, exogenous bias information, and parameter adjustment based on subjective confidence collectively converge into the decision integration process. In the context of this study, "decision integration" does not refer to the temporal judgment itself, nor is it equivalent to the comparison process described in the scalar expectancy theory (SET). Instead, it refers to the process of integrating multi-source information and its associated reliability cues to cope with uncertainty after a temporal judgment has already been formed. This process serves as the basis for organizing subsequent reporting, error correction, and behavioral output.

In terms of functionality, the self-assessment and feedback regulation pathways primarily provide substantive content input, whereas the confidence regulation pathway primarily provides parametric modulation. Consequently, although these three pathways are structurally parallel, they exhibit functional asymmetry.

In summary, this paper proposes a "Two-Stage, Three-Pathway Model" for temporal error monitoring. Building upon the computational foundations of Scalar Expectancy Theory, this model introduces a metacognitive perspective of evaluation and regulation. It divides the processing of temporal errors into two distinct stages: the generation of temporal errors and their subsequent evaluation and regulation. Through the specialized functions and integration mechanisms of its three pathways, the model provides a structured framework for the monitoring, evaluation, and decision-making integration processes inherent in temporal judgment. Furthermore, it establishes a theoretical foundation for future empirical investigations into the mechanisms of temporal error monitoring at behavioral, computational, and neural levels.

6 总结与展望

Introduction

Temporal error monitoring is a critical ability for individuals to detect, evaluate, and adjust errors during the process of time perception, serving an essential metacognitive function. This paper systematically reviews the core task paradigms, underlying mechanisms, and neurophysiological foundations of this field. Building upon this foundation, we propose an "Integrated Two-Stage, Three-Pathway Model" of temporal error monitoring. Overall, existing research has preliminarily revealed close links between temporal error monitoring and temporal judgment, feedback utilization, and subjective confidence. However, a systematic mechanistic explanation is still lacking regarding how temporal errors transition from generation to monitoring, how they are integrated, and how they ultimately influence behavioral regulation. Future research needs to further deepen the understanding of temporal error monitoring across neural mechanisms, developmental trajectories, and clinical applications.

First, the neural mechanisms of temporal error monitoring lack a systematic explanation; in particular, little is known about how key functional pathways dynamically collaborate across different stages or the cross-regional network mechanisms they depend on. In contrast, the field of general error monitoring has yielded relatively consistent findings:

Existing evidence suggests that the anterior cingulate cortex (ACC) plays a central role in error detection [**?**, **?**, **?**, **?**], while the dorsolateral prefrontal cortex (dlPFC) is more involved in error awareness and subsequent behavioral adjustment [**?**, **?**, **?**]. Furthermore, the ventral striatum (VS) plays an important role in feedback processing and reward prediction error handling [**?**, **?**, **?**]. However, these findings are primarily based on general error monitoring research, and their specific roles in temporal tasks remain unclear. There is currently a lack of direct evidence revealing how these brain regions coordinate during temporal tasks or how flexible switching is achieved at the network level. Consequently, future research should integrate the "Two-Stage, Three-Pathway Model" to further investigate whether primary error representation and subsequent metacognitive evaluation can be distinguished temporally, and whether the three pathways —self-evaluation, confidence regulation, and feedback regulation—possess relatively independent neural foundations. Specifically, it is necessary to explore how the self-evaluation and feedback regulation pathways form a bidirectional interaction to achieve timely utilization of error information and cross-trial strategy optimization. Simultaneously, research should examine how the confidence regulation pathway adjusts the weight allocation of external feedback under different confidence levels and how it is, in turn, influenced by that feedback. These interactions may depend on the flexible coordination of the frontoparietal network and involve dynamic switching between the timing-related network (TN) and the default mode network (DMN). Furthermore, such flexible inter-network collaboration may be realized through neural oscillatory activity; for instance, β-band oscillation patterns may support information synchronization across key brain regions, providing neurodynamic clues for temporal error monitoring [**?**, **?**, **?**]. Therefore, future studies should combine multimodal neuroimaging techniques (such as fMRI integrated with EEG/MEG) to capture collaborative patterns between brain regions in dynamic task environments and utilize neurodynamic modeling to parse the functional role of neural oscillations, thereby providing more systematic and robust evidence for the neural mechanisms of temporal error monitoring.

Second, while deepening the understanding of these mechanisms, future research should expand its developmental perspective and advance innovations in ecological paradigms. Existing evidence indicates that:

Temporal error monitoring relies on multi-level metacognitive regulatory mechanisms and their neural substrates, yet its dynamic evolution across different stages of the lifespan has not been systematically elucidated. Developmental studies have found that from childhood to adolescence, the amplitude of the error-related negativity (ERN) gradually increases, and the neural mechanisms of error monitoring expand from a primary reliance on the anterior cingulate cortex to broader regions including the mid-cingulate and posterior cingulate cortices [**?**, **?**, **?**]. This suggests that the maturation of this function is a relatively slow process that is not fully developed in early childhood. Conversely, in older populations, although error rates in task execution may be comparable to those of younger adults, error awareness and perception abilities decline significantly, accompanied by weakened associated neural signals [**?**, **?**]. This staged characteristic—continuous maturation in early life followed by differentiated degradation in awareness and neural signaling in later life—reveals that the core mechanisms of error monitoring do not develop or decline in a uniform manner, highlighting the necessity of longitudinal studies across age groups. Regarding the model proposed in this paper, future research should not only focus on age differences in the overall level of temporal error monitoring but also investigate developmental changes across different stages and pathways. Meanwhile, traditional experimental paradigms have limited explanatory power in multitask environments and resource-conflict conditions [**?**, **?**]. There is an urgent need to develop tasks with high ecological validity—using virtual reality, multitask scenarios, and real-time neurofeedback—to examine individual regulatory processes under conditions of uncertainty and interference. Such research would not only:

Help compare differences in temporal error monitoring across different age groups but also test the applicability of the "Two-Stage, Three-Pathway Model" in complex contexts. By advancing simultaneously from developmental and situational perspectives, it is possible to gain a deeper understanding of the adaptive characteristics of temporal error monitoring, providing a new theoretical basis for cognitive aging interventions and educational practices.

Finally, temporal error monitoring holds significant value for basic research and demonstrates high clinical potential for the diagnosis and intervention of psychiatric disorders such as depression and obsessive-compulsive disorder (OCD). Existing studies suggest that emotional disorders like depression are often accompanied by abnormal error monitoring, involving processes such as error detection, error sensitivity, and post-error adjustment. Corresponding neurophysiological indicators, such as the ERN, suggest that these individuals exhibit abnormalities in performance-monitoring-related processing [**?**, **?**, **?**]. For example, Sandre et al. (2023) found that a blunted ERN can predict the worsening of depressive symptoms, particularly in high-stress situations. Different psychiatric disorders present specific patterns in neural indicators of error monitoring: patients with OCD and anxiety often exhibit an enhanced ERN [**?**, **?**], whereas patients with Attention-Deficit/Hyperactivity Disorder (ADHD) show weakened ERN and Error Positivity (Pe) [**?**, **?**], and schizophrenia is associated with more widespread deficits in error-related signals, such as significantly reduced P300 and Theta activity [**?**, **?**]. Together, these findings suggest that functional abnormalities in the neural mechanisms related to temporal error monitoring may play an important role in the development of emotional disorder symptoms. This mechanism is expected to become a key target for neuromodulation and cognitive intervention. Based on this evidence, future research could further investigate the potential links between temporal error monitoring mechanisms and symptoms of psychiatric disorders within the framework of the "Two-Stage, Three-Pathway Model," focusing on whether different clinical groups exhibit distinct imbalance characteristics in error representation, self-evaluation, confidence regulation, or feedback utilization. This perspective helps distinguish whether relevant abnormalities primarily stem from the error representation itself or involve subsequent evaluation and regulation processes. Furthermore, exploring the effects of metacognitive training or neuromodulation methods on the functions of related regulatory networks could provide a theoretical basis for subsequent intervention studies.

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Metacognitive regulation and neurophysiological mechanisms of temporal error monitoring CUI Qian, JIA Yunxuan, LI Baike School of Psychology, Liaoning Normal University, Dalian 116029, China

Abstract

Temporal error monitoring is a critical metacognitive ability that refers to the cognitive process through which individuals detect, evaluate, and adjust potential deviations in time perception. This review systematically summarizes the core task paradigms, metacognitive regulatory mechanisms, and neurophysiological foundations in this field, with particular emphasis on the roles of self-evaluation, feedbackbased regulation, and decision confidence regulation in modulating the accuracy of temporal judgments.

Building on neural evidence from feedback-related negativity, β oscillations, and α oscillations, this review proposes a two-stage, three-pathway integrative model to account for the synergistic interactions among these

mechanisms. Current research remains limited by an insufficiently systematic understanding of the underlying neural mechanisms, a lack of developmental perspectives, and limited ecological validity of existing paradigms.

Future studies should integrate multimodal neuroimaging techniques with longitudinal developmental designs to develop more ecologically valid paradigms, clarify the dynamic coordination of large-scale brain networks and their oscillatory foundations, and facilitate the application of these findings to the diagnosis of mental disorders and cognitive interventions.

Keywords

temporal error monitoring, time perception, metacognition, neural mechanisms

Note: Figure translations are in progress. See original paper for figures.

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