# Abstract

Metacognition, the capacity to monitor and evaluate one's own cognitive states, encompasses a broad class of self-monitoring abilities. Temporal error monitoring (TEM) is one such ability, defined as the metacognitive process by which individuals assess the accuracy of self-generated temporal intervals without external feedback. As a tractable instance of metacognition, TEM offers a window into the computational and neural substrates of self-monitoring. Motor action timing serves as the experimental framework for investigating TEM: it generates a precise, internally-accessible error signal, the deviation between a produced interval and a target, and withholds external feedback, isolating metacognitive evaluation from externally-driven correction. This thesis presents a systematic investigation of TEM across complementary levels of analysis, integrating cross-species behavioral paradigms, motor-demand manipulations, and single-trial neural decoding via a transformer-based EEG architecture.

A first question concerned whether TEM is a conserved capacity across species and whether it is supported by shared or divergent strategies. Rats and humans were tested under matched conditions, with aligned trial structures, reward contingencies, and task rules, and were required to select the correct reward option based on the magnitude of their timing error relative to a target interval. Both species demonstrated reliable trial-by-trial error monitoring, establishing TEM as a shared capacity. The information supporting this monitoring, however, differed: rats relied more heavily on current-trial evidence, whereas humans drew more on accumulated trial history and learned reward rules. Critically, when task rule comprehension was equated across species, differences in TEM performance diminished, indicating that the shared monitoring capacity is shaped by strategy selection and rule use rather than by fundamental differences in timing ability.

TEM's conservation across species raised a further question: what information grounds metacognitive judgments about motor action timing in humans? Two competing hypotheses were formulated. Under the Clock Hypothesis, TEM precision decreases as clock signal noise increases, because additional motor variance disrupts the readout of the internal temporal representation. Under the Motor Hypothesis, motor variability improves TEM precision by providing a reference point between intended and actual motor actions. To dissociate these accounts, motor signal variance was experimentally manipulated by contrasting a button-press condition with a joystick-movement condition. Increased motor demand selectively impaired metacognitive precision without affecting motor action timing accuracy, supporting the Clock Hypothesis: individuals evaluate internal temporal representations rather than motor output signals. This aligns with a temporal metacognition account in which higher-order confidence judgments reflect a metacognitive readout of timing variability rather than motor execution.

Yet knowing that TEM draws on internal timing representations leaves unresolved whether metacognitive evaluation merely reads out the signals governing interval production or constitutes a neurally distinct process. The third study addressed this directly by decoding PCA-optimized single-trial EEG data using a Vision Transformer capturing theta (θ; 3–7 Hz), alpha (α; 8–12 Hz), and beta (β; 13–30 Hz) dynamics across both the motor action timing and TEM decision phases. Motor action timing accuracy was decodable from any single frequency band, consistent with independent frequency-specific oscillatory codes. Metacognitive inference, the alignment between objective timing performance and subjective error evaluation, by contrast, required the joint contribution of all three bands during ongoing motor action timing, with no single band sufficient alone. Furthermore, individuals whose pre-termination neural activity more reliably encoded metacognitive states exhibited greater TEM precision. Together, these findings establish metacognitive evaluation as a neurally distinct process, supported by higher-order multi-band integration.

Across the three studies, internal timing representations formed the core substrate of TEM, shaped by task rules, motor demands, and reward expectations. Impaired TEM precision under higher motor demands supports a clock-based account, while the dissociation between motor timing codes and multi-band metacognitive inference indicates that TEM relies on higher-order neural mechanisms distinct from performance itself.

**Keywords:** metacognition, temporal error monitoring (TEM), motor action timing, interval production, EEG decoding, transformer architecture.