Proceedings of ICMMGH 2026 Symposium: Cell and Molecular Biology: Understanding Immune Cell Functions
DOI: 10.54254/2753-8818/2026.PJ30854

The Double-Edged Nature of Delay: Toward a Functional Latency Window in Neurorehabilitation and Brain–Machine Interaction

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Abstract. Delay pervades human–machine systems—from synaptic transmission and axonal conduction to sensing, computation, and actuation. Traditionally viewed as a nuisance to minimize, latency can instead serve as a functional design parameter when it is internal, structured, and predictively compensated. Theoretically, the FLW connects timing-dependent plasticity and predictive coding in neural systems to an analysis of stability in delay-differential equations which shows that moderate delays with structure can stabilize dynamics rather than break them. Practically, this framework informs delay-aware design in brain-computer interfaces and rehabilitation robotics wherein user-experienced delay has to be minimized so as to retain implicit learning and agency. In contrast, internal controller delay can be structured to enhance stability and adaptation. By integrating neuroscience, psychophysics, and control theory, this review proposes delay as both a constraint and a resource, offering a biologically grounded principle for building robust, human-compatible feedback systems.

Keywords: Human-machine interaction, Predictive coding, Spike-timing-dependent plasticity, Delay differential equations, Rehabilitation robotics

1. Introduction

Delay is inevitable. Neural conduction, synaptic transmission, sensor sampling, and actuator inertia introduce cumulative latencies from tens to hundreds of milliseconds [1]. In human–machine interaction, latencies arise from two distinct sources. First, perceptual latency varies across modalities: vision requires approximately 100 ms to reach a stable cortical representation, audition and touch are faster, and olfaction operates on predictive pathways that bypass thalamic relays [2,3]. Even within the motor domain, excitation–contraction coupling and tendon elasticity produce an electromechanical delay (EMD) of 30–80 ms [4].

Second, internal computational or communication delays occur within the controller itself. In robots parameters of such a delay accumulate through sensing and digital filtering and transmission jitter and actuator settling wireless communication can add tens of milliseconds variability [5] hence total loop delay sets a hard lower bound for real-time control when these internal latencies are predictable modeled and compensated they can serve as structured delays in fact enhancing stability

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and coordination. The present study concerns exclusively this latter class of delay. The central question is not how to eliminate all delay, but how to exploit invisible, internal delay to achieve stable and adaptive performance.

At the micro level, this paper reviews how biological systems cope with timing through spike-timing-dependent plasticity (STDP) and predictive coding to address this question. At the system level, previous analyses of delay-coupled oscillators, such as van der Pol systems, demonstrate that introducing finite transmission delay can expand stability regions and even suppress oscillations.

2. Neural use of delay: prediction and plasticity

2.1. Predictive coding

Predictive coding interprets perception as hierarchical inference, as shown in Figure 1, where higher cortical levels send predictions to lower areas while discrepancies propagate upward [6].

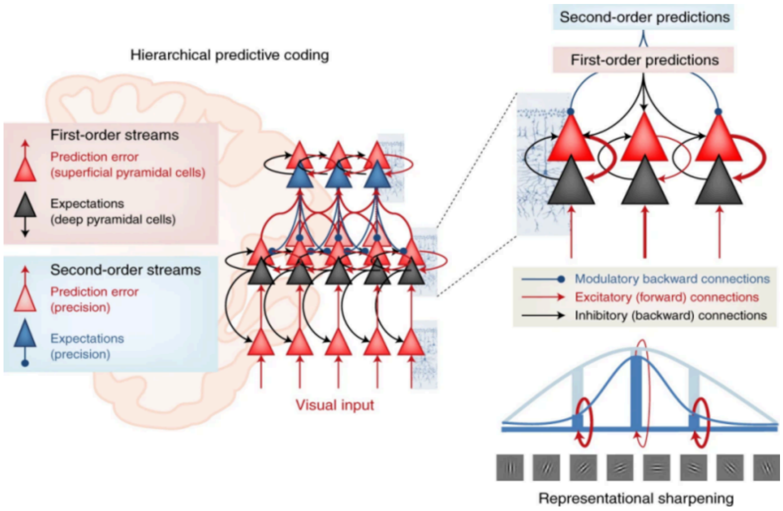

Figure 1. Hierarchical predictive coding [7]

This framework is inherently dependent on latency; higher cortical regions must project predictions that are slightly ahead of the sensory evidence that is received, this ensures that feedback signals are within the window of neural processing that is approximately 50-150 ms. In brain–computer interfaces (BCIs), this idea is expressed as "intent decoding" preceding actual movement; preemptive decoders that are trained on previous activity can compensate for 100–200 ms of transmission delay [8]. Instead of taking immediate action, effective BMI control involves synchronizing the dynamics of the decoder with the user's internal forecasting period.

Mathematically, predictive coding can be formalized as a delayed feedback estimator:

$$\hat{s}_{t+1} = \hat{s}_t + K \bullet \epsilon_{t-\tau} \tag{1}$$

where τ represents processing delay and K a precision-weighted gain. Small τ preserves hierarchy between prediction and feedback; excessive τ yields oscillatory corrections and perceptual desynchrony. Optimal adaptation occurs when τ matches the system's intrinsic integration constant, yielding minimal steady-state prediction error [9].

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2.2. Spike-timing-dependent plasticity

At the synaptic level, delay is responsible for the causality. Spike-timing-based plasticity (STDP) changes the weight of a synapse based on the order of preceding and subsequent spikes [10].

Long-term potentiation (LTP) occurs when presynaptic firing precedes postsynaptic activation by less than about 20 ms, while the inverse sequence produces long-term depression (LTD). This biphasic learning rule defines a micro-scale optimal window for information transfer, typically modeled as

$$W(\Delta t) = \begin{cases} A_{+}e^{-\Delta t/\tau_{+}}, & \Delta t > 0 \\ -A_{-}e^{-\Delta t/\tau_{-}}, & \Delta t < 0 \end{cases} \quad (2)$$

where τ_{+} and τ_{-} represent potentiation and depression constants, respectively.

This three-factor rule--pre-, post, and neuromodulatory timing-- illustrated in Figure 2, connects cellular plasticity with reinforcement learning and defines the neural substrate for delay-based credit assignment.

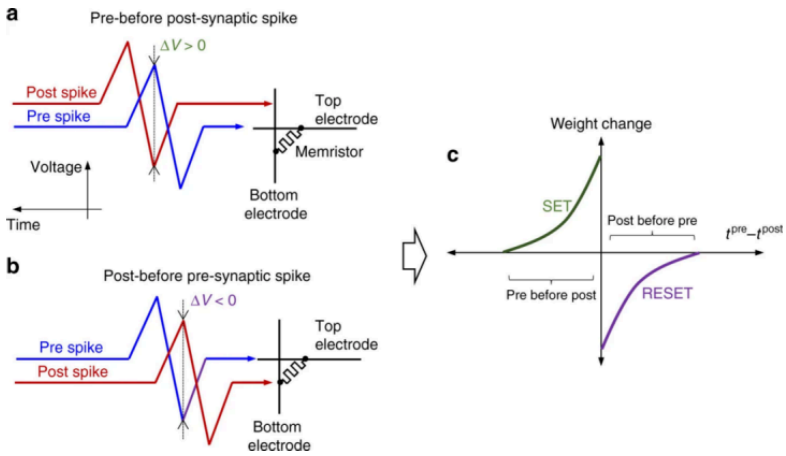

Figure 2. STDP implementation [11]

Memristive synapses in ferroelectric transducers replicate the behavior of STDP and modulate it with a temporal window, this provides a physical representation of the timing-sensitive learning in neuromorphic devices [12]. Such devices demonstrate that a modest, structured delay can enhance learning stability, supporting the same principle observed in biological circuits.

2.3. Implications for closed-loop BCIs

In invasive and non-invasive BCIs, feedback delay critically shapes user adaptation [13]. Introducing short, predictable delays (≈ 50–150 ms) can improve anticipatory synchronization between cortical activity and effector motion [14]. Aligning artificial feedback within such windows preserves co-adaptation and stability, transforming delay from a nuisance into a tunable parameter.

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3. Delay at the behavioral level: functional windows

3.1. Human evidence

Psychophysical and behavioral studies show that human sensorimotor control tolerates only a bounded range of feedback delay. When visual feedback approaches ~400 ms and beyond, performance and the sense of agency drop sharply, participants abandon smooth predictive control for “act–wait–see” strategies with higher error variance [15]. EEG markers converge with this behavioral shift, indicating a breakdown of predictive mechanisms [16].

In continuous tracking and virtual-reality tasks, visuomotor accuracy and smoothness deteriorate monotonically with increasing delay, but the minimum typically sits around ~100–150 ms, consistent with visual loop constraints [17,18]. Across studies, agency ratings are largely preserved up to ~300–400 ms and then deteriorate, aligning subjective control with the behavioral breakpoint [19]. Neuroimaging further shows that moderate, predictable delays enhance frontoparietal coherence—a signature of active prediction—whereas long or variable delays recruit prefrontal monitoring associated with conscious error awareness [20].

3.2. Multisensory binding and temporal recalibration

Human perception maintains a multisensory temporal binding window (TBW) on the order of ~±100 ms for audiovisual events, within which modest asynchronies are fused; outside it, inputs segregate [21]. The prolonged exposure to consistent offsets causes the temporal recalibration, which in turn shifts the perceived simultaneity towards the experienced lag. Converging neuroimaging suggests that parietal, temporal, parietal, and cerebellar regions participate in re-setting the temporal order of sensorimotor events [22]. In BCI contexts, users likewise adapt to consistent feedback delays. While direct evidence for systematic premotor/parietal phase advancement during BCI training remains limited, studies of sensorimotor recalibration show latency-dependent shifts in preparatory/sensory potentials, and mainstream BCI frameworks posit internal models that compensate for fixed delays [23].

By analogy, the multisensory TBW serves as a phase-margin-like buffer for perception: bounded and predictable latency helps sustain coherent multisensory experience, just as engineered controllers maintain positive phase margin for stability.

4. Control-theoretic view: delay and stability

A pure time delay enters the loop as $e^{-s\tau}$, adding a frequency-dependent phase lag $-\omega\tau$ that generally reduces phase margin and can precipitate oscillations if left uncompensated. Yet in nonlinear coupled oscillators, delay can create stable regimes that do not exist in the zero-delay limit and rearrange bifurcation structure in beneficial ways [24].

This stabilizing effect of delay has been most clearly illustrated in canonical nonlinear systems such as the van der Pol oscillator. For two van der Pol oscillators with delayed coupling, both method-of-averaging analysis and direct DDE simulations show that nonzero τ induces stability switches, Hopf onsets, and even amplitude death in parameter regions where the zero-delay system sustains limit cycles [25]. In short, adding delay can stabilize or synchronize motherwise unstable modes Extending to two-degree-of-freedom delay-coupled van der Pol systems, normal-form calculations reveal stability switches as τ varies and the emergence of double-Hopf bifurcations, yielding richer but designable dynamics [26].

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While delay reduces phase margin in the frequency domain, in the nonlinear time domain, a modest, predictable delay functions as a low-pass on corrective interactions, attenuating high-frequency chatter yet preserving slow coordination and thereby defining a functional (K, τ) window for robust entrainment [27].

When the controller predicts one horizon, delay-coupled models admit in-phase or phase-advanced locking that is more robust than instantaneous feedback, aligning with behavioral anticipatory synchronization reported in human–machine coordination. Practically, operate in a short, predictable delay regime and supply the controller with prediction, leveraging the same mechanism that makes delay-coupled oscillators more rather than less stable when (K, τ) live in the right window.

5. Toward delay-aware rehabilitation design

In rehabilitation robotics, delay should be minimized where it is felt and tuned where it is controlled. On the user side, reducing end-to-end visual latency below 100 ms and keeping jitter low reliably enhances implicit adaptation and agency, while small, predictable lags can serve as graded challenges during postural training [28,29]. On the controller side, delay becomes a design variable. Predictive, delay-aware control—via Smith predictors, MPC, or TDE variants—uses one-horizon-ahead estimation to recover phase margin and render residual latency perceptually invisible [30]. In gait exoskeletons, low-jitter phase anchoring and predictive torque control absorb computation and communication delays, producing smoother transitions and stable entrainment [31]. Across tasks, a single rule applies: minimize user-experienced delay; structure and compensate internal delay.

6. Conclusion

Neural conduction and synaptic transmission introduce inevitable temporal offsets. At the same time, biological systems cope with them through mechanisms like spike-timing-dependent plasticity and predictive coding, turning millisecond-scale lags into substrates for learning and anticipation. Complementing behavioral evidence, theoretical analyses of delay-coupled oscillators demonstrate that finite, structured delays can expand stability regions and suppress undesired oscillations. This framework suggests delay-aware control strategies that balance human perception and system stability when applied to rehabilitation and brain-computer interfaces. Together, from synaptic transmission to rehabilitation robotics, exploiting internal latency provides a biologically grounded pathway toward robust, adaptive human–machine systems.

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