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Interference is Controlled by Prediction

The Ze apparatus does not decide what to measure, but whether coherence is permitted to manifest

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Abstract

Interference phenomena are commonly understood as consequences of path indistinguishability and coherence constrained by the availability of which-path information. While delayed-choice and quantum eraser experiments have demonstrated that interference can be restored or suppressed depending on measurement context, such effects are typically implemented through discrete, externally imposed experimental configurations. In this work, propose a delayed-choice interferometric scheme in which interference visibility is regulated adaptively via predictive estimates of informational accessibility. The proposed architecture introduces an operational measure of predictability derived from ensemble-level intensity statistics, which is used to control downstream interferometric elements after the system has traversed the interferometer. This design preserves the delayed-choice character of the experiment while avoiding any modification of standard quantum mechanical formalism or assumptions of retrocausality. Predictability is treated as an informational control parameter rather than as an intrinsic property of the system's past evolution. The scheme builds upon established complementarity relations and information-theoretic approaches to coherence and decoherence, extending them toward adaptive, feedback-based control of interference. The proposal is experimentally accessible using classical or semi-classical optical components and does not rely on single-particle detection. By reframing interference as a dynamically regulated informational regime, the work provides a bridge between foundational concepts of quantum measurement and practical architectures for coherence control.

Keywords: Interference; Complementarity; Delayed-Choice Experiments; Which-Path Information; Predictability.

Introduction

Interference phenomena and their dependence on path indistinguishability have played a central role in the development of wave optics and quantum mechanics. From early optical interference experiments to modern quantum interferometry, the appearance or disappearance of interference fringes has been understood as a manifestation of coherence constrained by the availability of which-path information. This relation has been formalized through quantitative complementarity relations linking fringe visibility to path distinguishability, establishing fundamental limits on the simultaneous accessibility of mutually exclusive properties.

Subsequent theoretical and experimental developments refined this picture by demonstrating that interference is not irreversibly destroyed by local interactions alone, but rather depends on whether which-path information is, even in principle, accessible. Quantum eraser experiments showed that interference can be recovered by rendering path information unavailable, while delayed-choice interferometric schemes demonstrated that the manifestation of wave-like or particle-like behavior depends on the final measurement context rather than on the system's prior evolution. Together, these results suggest that interference is not an intrinsic property of a system's history, but an emergent feature shaped by informational constraints imposed at the level of measurement.

Despite these advances, most realizations of delayed-choice and quantum eraser experiments rely on discrete experimental configurations: the apparatus is switched between interference-permitting and interference-suppressing regimes by externally imposed choices. In such settings, distinguishability is treated as a fixed property determined by the experimental layout, rather than as a dynamically regulated quantity. As a consequence, interference control remains structurally defined rather than adaptively modulated.

In parallel, information-theoretic approaches to quantum mechanics have emphasized the role of predictability, distinguishability, and decoherence as operational quantities characterizing the flow and accessibility of information. Quantitative relations between predictability, distinguishability, and interference visibility have been rigorously formulated, highlighting that complementarity can be understood as a constraint on information acquisition rather than a purely ontological feature of quantum systems. However, these insights have rarely been implemented in experimental architectures where predictability itself participates in a feedback or control loop.

In this work, propose a delayed-choice interferometric scheme in which interference visibility is regulated adaptively through predictive estimates of informational accessibility. Instead of toggling between fixed measurement configurations, the system continuously evaluates an operational measure of predictability derived from ensemble-level intensity statistics and uses this estimate to control downstream elements of the interferometer. Crucially, this control is implemented after the system has traversed the interferometric paths, preserving the delayed-choice character of the experiment while avoiding any modification of standard quantum formalism.

The present proposal is conceptually aligned with the Ze system framework, which formulates coherence and observation as predictive and informational processes rather than purely measurement-driven effects (Tkemaladze, 2026). Within this perspective, interference is reinterpreted as a controllable informational regime, emerging from the dynamic management of predictability rather than from static experimental constraints.

By framing interference as an object of adaptive informational control, the proposed architecture extends established delayed-choice and complementarity paradigms toward an engineering-oriented approach to coherence. This shift opens a route to experimental investigations in which measurement is not merely a passive act of registration, but an active process shaping the informational structure through which interference emerges.

Interference, the hallmark phenomenon of wave-particle duality, has traditionally been explained as a consequence of three principal factors: the coherence properties of the source (Mandel & Wolf, 1995), the precise geometry of the interferometer, and the presence or absence of which-path information (WPI) (Scully & Drühl, 1982). The prevailing Copenhagen interpretation posits that a particle's wave-like or particle-like behavior is not an intrinsic property but becomes defined upon measurement. This foundational concept was dramatically extended by the quantum eraser (Scully et al., 1991) and delayed-choice experiments (Wheeler, 1978; Jacques et al., 2007). These paradigms demonstrated that interference is not a property of the past trajectory of a quantum system but rather depends critically on the predictable availability of path information at the stage of final measurement, even if that availability is decided after the particle has ostensibly traversed the apparatus.

In a quantum eraser, the deliberate erasure of WPI, stored in an ancillary quantum system or the environment, can restore an interference pattern that was previously washed out. The delayed-choice variant elegantly underscores that it is not the physical act of "looking" but the information-theoretic condition—whether the experimental configuration allows one to, in principle, infer the path—that dictates the observable outcome. As articulated by Jacques et al. (2007), the photon "decides" whether to behave as a wave or a particle only upon its detection, based on the complete experimental configuration.

However, a critical examination of existing experimental architectures reveals three significant limitations. First, the choice between an "interference" or a "which-path" configuration is typically discrete. A beamsplitter is either present or absent, a polarizer is set to a specific angle, or a quantum eraser operation is either performed or not (Kim et al., 2000). Second, control over the emergence of interference is exercised through structural modification of the apparatus—changing optical elements, inserting detectors, or altering entanglement partners. It is not an adaptive, continuous process but a binary selection of setup. Third, and most importantly, the predictability of the eventual information availability is treated as a fixed, binary parameter rather than a continuously tunable variable that can govern the degree of interference. The system transitions sharply between a regime of full fringe visibility and no fringes.

This leads to the key gap in current research: there is no established experimental framework where the visibility of quantum interference is regulated continuously and dynamically by a quantitative degree of predictable future information accessibility, rather than by the definitive, discrete fact of a measurement setting. In other words, can we construct a scenario where we dial not between "path known" and "path unknown," but between "path information will be available with probability P," and observe the interference pattern vary smoothly as a function of P?

Such a framework would bridge the purely information-theoretic interpretations of quantum mechanics and its observable statistical phenomena. It reframes the question from "Is which-path information available?" to "How predictable is its future availability?" This shift aligns with emerging informational interpretations of quantum foundations (Zeilinger, 1999; Brukner & Zeilinger, 2009) and resonates with concepts in quantum causality (Brukner, 2014). A preliminary theoretical model supporting this direction has been proposed, suggesting that interference visibility V can be linked to the predictive certainty C about the final information state, following a relation of the form:

$$V = V_0 * \sqrt{1 - C^2}$$

where V_0 is the maximum visibility for a perfectly coherent source, and C ranges from 0 (complete unpredictability of which-path data) to 1 (complete predictability). This model, while requiring empirical validation, posits a continuous trade-off, contrasting with the sudden wave-function collapse implied by discrete measurement. Recent work on weak measurements and quantum trajectories (Williams & Jordan, 2008) provides tools to probe such intermediate regimes, while studies on coherence as a resource in quantum thermodynamics (Lostaglio et al., 2015) highlight the value of controlling it continuously. Therefore, developing an experimental paradigm to test the continuous control of interference via prediction would not only address a conceptual gap but also provide a novel methodological tool for quantum information science.

Central Hypothesis

The experimental paradigms of delayed-choice and quantum erasure have established a profound, if counterintuitive, tenet: the observable behavior of a quantum system (wave-like interference vs. particle-like which-path determination) is not fixed by its past but by the future configuration of the measurement apparatus (Wheeler, 1978; Jacques et al., 2007). This result underscores an information-theoretic reality over a classical dynamical one. Building upon this foundation, we posit a more granular and adaptive principle for the control of quantum phenomena. The central hypothesis of this work is as follows:

The visibility of quantum interference can be adaptively and continuously regulated by a predictive estimate of the future accessibility of which-path information (WPI), even when the definitive experimental choice that realizes or withholds that information is physically implemented after the quantum particle has irreversibly traversed the interferometric paths.

This hypothesis refines and extends the standard delayed-choice narrative in three critical ways, each addressing limitations noted in the background and designed to pre-empt common criticisms. It is crucial to emphasize from the outset what the hypothesis does not propose to avoid misinterpretation.

First, no new quantum dynamics is introduced. The proposed mechanism operates entirely within the established framework of standard quantum mechanics, unitary evolution, and Born rule probability calculation (Nielsen & Chuang, 2010). The system's evolution remains governed by the Schrödinger equation; the innovation lies in the parameterization of the measurement setting. Instead of treating the final measurement basis as a discrete, fixed variable (e.g., project onto interference fringes or path eigenstates), we propose treating the probability distribution over possible future measurement bases as a continuous control parameter. The system's state evolves in a superposition that entangles it not with a definite future setting, but with a probabilistic distribution of possible future settings, the predictability of which is under external control. This approach is conceptually aligned with the formalism of quantum operations and instruments (Davies & Lewis, 1970; Chiribella et al., 2008), where a measurement is described by a set of transformations conditioned on classical outcomes.

Second, causality in the relativistic sense is not violated. The control signal that adjusts the predictive parameter—the knob that sets the probability p of eventually performing a which-path measurement—may be timelike-separated from the particle's entry into the interferometer. However, the specific, irreversible choice of which measurement is actually performed (e.g., the random number generator output, the final beamsplitter setting) must remain spacelike- or future lightlike-separated from the particle's passage at the path-splitting stage, as in standard delayed-choice experiments (Ma et al., 2016). We manipulate the predictability of an event from the particle's effective perspective, not the event itself retroactively. This distinction is subtle but paramount. The temporal ordering ensures no superluminal signaling is possible, preserving compatibility with special relativity (Salart et al., 2008). The hypothesis is thus one of retrodiction or post-selection based on a pre-established probabilistic rule, not retrocausation.

Third, the proposed control is enacted at the level of ensemble statistics, not individual quantum events. For a single photon or particle, the outcome (detection at a specific point, or registration in a specific path) remains probabilistic and irreducible. The hypothesis concerns the visibility of the interference pattern, a statistical property extracted from many repetitions of the experiment under identical predictive conditions. As we adjust the predictive parameter (e.g., the bias of a future random choice), the calculated probability distribution for detection events across the ensemble changes continuously. Consequently, the observed fringe contrast, calculated from this distribution, should vary smoothly from a maximum (when WPI future accessibility is perfectly unpredictable, p=0.5 in a balanced random choice) to a minimum (when it is perfectly predictable, p=0 or 1). This perspective connects directly to the quantum-to-classical transition understood through decoherence (Zurek, 2003): increasing the predictability of WPI is akin to increasing the effective coupling to a future "environment" (the measurement apparatus) that will, with known likelihood, acquire information.

The mechanism can be conceptualized using a simple theoretical model. Consider an interferometer where a quantum system (e.g., a photon) is put into a path superposition. Its state becomes entangled with a "control qubit" that does not directly store WPI but instead encodes the probability distribution for a future choice. For instance, the control qubit is prepared in a state: $|\Psi\_c\rangle = \sqrt{(1-\alpha)}|Choice\_A\rangle + \sqrt{\alpha}|Choice\_B\rangle$, where α is a tunable parameter. Choice_A leads to a final measurement in the interference basis, Choice_B to a measurement in the which-path basis. The predictability of the which-path outcome is a function of α. Tracing out the control qubit before its measurement yields a reduced density matrix for the photon whose off-diagonal coherence terms are scaled by a factor f(α). The fringe visibility V is proportional to |f(α)|. In a symmetric model, $f(\alpha) = 2\sqrt{(\alpha(1-\alpha))}$, which is 1 for α=0.5 (maximal unpredictability) and 0 for α=0 or 1 (maximal predictability). This model, a direct extension of standard quantum eraser formalisms (Englert, 1996), provides a clear, continuous relationship: $V \propto \sqrt{[P(interf) * P(path)]}$, where P are the probabilities of the future measurement choices.

This hypothesis bridges the conceptual gap identified earlier. It moves beyond the discrete, structural control of interference to propose a form of adaptive predictive control. The "knob" one turns is not on a beamsplitter but on the source of randomness governing a future decision. It elevates predictability—a classical statistical concept—to the status of a fundamental governor of quantum behavior. Experimental validation would require a delayed-choice apparatus with a tunable random decision generator, where the bias of this generator (the predictive parameter) is varied systematically while measuring the resulting interference pattern. Success would demonstrate that quantum systems respond not merely to what will happen, but to how definitely we can predict what will happen, offering a novel operational perspective on the role of information in quantum mechanics.

Conceptual Framework

Predictability as an Operational Quantity

The central hypothesis necessitates a precise and operational definition of the governing variable: predictability. In the context of quantum interference and which-path information (WPI), predictability has often been conflated with the actual availability of information or treated as an abstract concept. Here, we propose a distinct, operational treatment. Predictability is not interpreted as a quantum mechanical observable of the system itself, nor is it directly a measure of entanglement or decoherence (Englert, 1996; Dürr et al., 1998). Instead, it is defined as an ensemble-level, classical statistical parameter that quantifies the expected future accessibility of WPI from the perspective of an external agent or a defined control protocol.

This distinction is critical. In a standard quantum eraser, the presence or absence of WPI is a binary property of the total quantum state (system + ancilla). Our framework introduces a prior, classical layer: a tunable probability distribution over the type of future measurement that will be performed on that total state. Predictability (P) in this sense refers to the skew of this distribution. If a future random choice between an "interference measurement" and a "which-path measurement" is perfectly balanced (e.g., a 50/50 beam splitter in the control channel), the predictability of the eventual information accessibility is minimal ($P \to 0$). If the random choice is heavily biased (e.g., a 95/5 split), the predictability is high ($P \to 1$), as one can reliably forecast which type of measurement will occur.

To formalize this, we introduce a measurable functional, ΔF, defined at the ensemble level. Consider an idealized two-path interferometer (e.g., a Mach-Zehnder). For a large ensemble of identically prepared systems, one can—under a hypothetical direct which-path measurement—estimate the probabilities P_1 and P_2 for a particle to be found in path 1 or path 2, respectively. These probabilities are operationalized through observed detection statistics over many trials. We define the path predictability functional as:

$$\Delta F = | P_1 - P_2 |$$

where $0 \leq \Delta F \leq 1$. This quantity, sometimes termed the "path distinguishability" or predictability in wave-particle duality relations (Greenberger & Yasin, 1988; Englert, 1996), measures the maximum a priori which-path knowledge one could potentially gain from an ideal measurement on the ensemble. Crucially, in our framework, ΔF is not a property derived from a quantum state in a single trial but an ensemble statistic that serves as an indicator. It indicates the degree to which the experimental configuration is predisposed to yield WPI. When $\Delta F = 0$ ($P_1 = P_2$), the paths are equally probable, and no predictive advantage exists about which path a particle would take if measured. When $\Delta F = 1$, one path is certain, representing maximal predictive knowledge.

The key innovation is linking this abstract ΔF to a directly measurable experimental quantity without performing an actual which-path measurement, which would destroy interference. This is achieved through a statistical proxy. In an interferometric setup, the distribution of detected particles at the output screen or detector array forms an interference pattern characterized by its intensity I(x). The standard deviation (σ) of this intensity distribution, or more precisely, the contrast in the variations of I(x) across the detection plane, serves as a surrogate measure. For a perfect, high-visibility sinusoidal fringe pattern, the intensity varies greatly across positions, leading to a relatively high σ. As the fringes wash out, the intensity distribution flattens, and σ decreases towards the standard deviation of a constant (or single-slit) pattern.

Therefore, in the experimental implementation, we posit the following operational approximation:

$$\Delta F\_estimated \approx 1 - (\sigma\_observed / \sigma\_max)^\gamma$$

Here, σ_observed is the measured standard deviation of the spatial intensity distribution in a given experimental run with a specific predictability setting. σ_max is the maximum standard deviation achieved when the future information accessibility is perfectly unpredictable (yielding maximal fringe contrast). The exponent γ is a scaling factor of order 1, dependent on the specific interferometer geometry and detection model, which can be calibrated. The term (σ_observed / σ_max) effectively acts as a normalized measure of fringe contrast or visibility (V). This yields the familiar duality-like relation in an operational form: $\Delta F\_estimated^2 + V^2 \approx 1$, consistent with the theoretical work of Englert (1996) and others, but here with each term defined through ensemble statistics rather than quantum operators for a single system.

Crucial defensive formulation: The parameter σ (standard deviation of intensity) is not interpreted as a quantum observable in the traditional sense (i.e., the expectation value of a Hermitian operator on a single system). It is explicitly treated as an operational estimator of ensemble-level informational openness. It is a classical statistical measure computed a posteriori from a large set of detection events. This avoids philosophical pitfalls related to assigning properties to individual particles and keeps the framework strictly within the bounds of the statistical interpretation of quantum mechanics (Ballentine, 1970). The predictability P (or its proxy $\Delta F\_estimated$) is a control parameter set by the experimentalist via the bias of a future random choice generator; it determines the conditions under which the ensemble is collected. The resulting σ is the outcome statistic that reveals how the quantum ensemble responded to that predefined level of predictive constraint.

This operational approach finds resonance in modern information-theoretic treatments of quantum foundations. The use of classical statistical measures to bound quantum behavior is evident in recent derivations of uncertainty relations (Coles et al., 2017) and in the resource theory of coherence, where measurable witnesses are used to quantify superposition (Baumgratz et al., 2014). Our use of σ as a proxy aligns with this philosophy, providing a practical bridge between a conceptual control parameter (predictability) and a raw experimental datum.

Furthermore, this framework seamlessly incorporates the delayed-choice paradigm. The control parameter P (defining the bias of the future random choice) is set before each experimental run or block of runs. The quantum system traverses the apparatus while the final measurement setting remains undetermined but governed by a known probability distribution. The ensemble statistic σ is then compiled from all events, irrespective of which specific measurement (interference or which-path) was ultimately performed on each individual particle. This procedure ensures that the observed σ reflects the predictive conditions of the entire ensemble, not post-selected sub-ensembles. It validates the hypothesis that the quantum statistical outcome is continuously shaped by the predictability of future information accessibility, not just by its definitive presence or absence.

Relation to Complementarity and Decoherence

The proposed framework does not exist in a conceptual vacuum but is deeply rooted in two pillars of modern quantum theory: the formal quantitative statement of wave-particle complementarity and the dynamical theory of decoherence. Our approach synthesizes elements from both to construct a novel perspective on the active control of quantum phenomena via information prediction.

Foundation in Formal Complementarity

The cornerstone for any quantitative discussion of interference and which-path information is the duality relation formalized by Englert (1996). This seminal work established an inequality for two-path interferometers:

$$V^2 + D^2 \leq 1$$

Here, V is the visibility of the interference fringes, a direct measure of wave-like behavior, and D is the path distinguishability, quantifying the maximum amount of which-path information that can be obtained, representing particle-like behavior. This inequality provides a precise mathematical expression of Bohr's complementarity principle (Bohr, 1928), stating that the manifestations of wave and particle nature are mutually exclusive yet complementary. This relation has been experimentally verified in various systems, from photons (Jacques et al., 2008) to atoms (Dürr et al., 1998) and large molecules (Eibenberger et al., 2013).

Our work fundamentally relies on this inequality as a descriptive boundary for possible experimental outcomes. However, the novelty lies in the procedural role assigned to the distinguishability parameter D. In traditional experiments, D is typically a fixed consequence of the apparatus design: a fixed beamsplitter ratio, a static marking scheme, or a predetermined erasure setup. It is a structural property of a given experimental run. In our framework, D is not fixed but predicted and utilized within a control loop.

We treat D—or more precisely, its operational ensemble proxy, the predictability ΔF defined in Section 3.1—as a setpoint. The experimentalist defines a target value for path predictability (D_target) by tuning the bias of a future random decision generator. The system, evolving under the impending but unresolved measurement dictated by this bias, produces an interference pattern. The measured visibility V_observed then becomes the output of this process. The duality relation $V\_observed^2 + D\_target^2 \leq 1$ acts as a constraint that the experiment must satisfy, validating the consistency of the quantum formalism. This active role transforms D from a passive, structural property into an input control variable. This perspective is prefigured in theoretical models where distinguishability is treated as a variable parameter (Englert et al., 2017), but it is operationalized here through a delayed-choice architecture with a tunable random element.

Integration with Informational Decoherence

The second pillar is the theory of decoherence (Zurek, 2003; Schlosshauer, 2005). Decoherence explains the suppression of interference not through a fundamental collapse mechanism, but through the unitary but irreversible leakage of quantum information from a system into its environment. When a system in a superposition becomes entangled with environmental degrees of freedom, the phase information necessary for interference becomes dispersed and practically inaccessible, leading to an effectively classical mixture from the perspective of the system alone. The key quantity is the rate of this information loss, which depends on the system-environment coupling strength.

Our framework provides an informational and predictive reinterpretation of this process. The "environment" in a delayed-choice experiment is effectively the future measurement apparatus, including the random choice device. The predictability of the future information accessibility is analogous to the strength of the effective coupling to this "future environment." A highly predictable outcome (e.g., a 95% chance of performing a which-path measurement) means the system's state becomes strongly correlated (entangled) with a highly certain future. This is information-theoretically equivalent to rapid decoherence, leading to low visibility. Conversely, a perfectly unpredictable future (a 50/50 chance) represents a weak, ambiguous correlation, preserving coherence and allowing high visibility.

This connection is not merely metaphorical. The decoherence functional formalism (Gell-Mann & Hartle, 1990), which tracks the loss of coherence between histories, can be adapted to our scenario. The predictability parameter P (or D_target) directly influences the off-diagonal terms in the system's reduced density matrix, calculated by taking a partial trace over the future "control" degrees of freedom whose state is a probabilistic mixture. The decoherence factor, which scales these off-diagonal terms, becomes a continuous function of P (Tkemaladze, 2023). Thus, controlling predictability is operationally equivalent to controlling the onset and degree of environmentally induced decoherence, but with the "environment" being a deliberately crafted, information-bearing future event.

Interference as a Controlled Informational Regime

The synthesis of these foundations leads to the core conceptual shift proposed by this work. Interference ceases to be viewed as a passive observational result—something we merely observe or fail to observe based on a fixed setup. Instead, it is reframed as a managed informational regime.

In this new view:

1. **The Control Input is Predictive Information**: The primary dial is the classical statistical predictability (D_target/P) of the type of information (wave or particle) that will be extracted in the future.
2. **The Quantum Process is Adaptive**: The quantum system's evolution (in an ensemble sense) adapts to this predictive landscape. It is not that a single particle "knows" the future, but that the statistical distribution of many particles is shaped by the predictable correlations established between the system's path and the future measurement setting.
3. **The Output is Tunable Coherence**: The resulting interference visibility V is the observable output, which can be smoothly tuned from maximum to minimum by varying the control input. The system operates in a continuum of regimes between pure coherence and full decoherence.
4. **The Mechanism is Consistent**: This control is enacted without violating causality or single-particle unitarity. It operates through the legitimate mechanism of post-selection on ensembles prepared under known probabilistic future conditions, a well-established technique in quantum optics (Pittman et al., 1995) and weak measurement (Aharonov et al., 1988).

This perspective bridges the often-separated domains of quantum foundations and quantum control theory (Wiseman & Milburn, 2009). It suggests that complementarity is not just a limitation but a principle for engineering. By treating the predictability of information acquisition as a resource, we can design experiments that dynamically steer the collective quantum behavior of an ensemble. This has potential implications for quantum technologies where the preservation or suppression of coherence needs to be managed dynamically, such as in quantum metrology protocols sensitive to decoherence (Giovannetti et al., 2006) or in quantum communication scenarios where information must be selectively revealed.

In conclusion, the framework presented here does not contradict the established theories of complementarity and decoherence but rather integrates them into an active, predictive control scheme. It demonstrates that the boundary between wave and particle behavior is not a wall to be toppled, but a dial to be turned, governed by the predictability of information.

Experimental Architecture (Ze Apparatus)

To empirically validate the hypothesis that interference visibility is continuously controlled by the predictability of future which-path information (WPI) accessibility, a dedicated apparatus, designated the Ze (Zero-effect predictability) apparatus, was designed and constructed. Its architecture integrates a standard optical interferometric core with a real-time predictive control loop, implementing a true delayed-choice paradigm. The design prioritizes operational clarity, causality preservation, and the capacity for continuous parameter tuning over ultimate single-photon sensitivity.

Optical Core

The light source is a high-intensity light-emitting diode (LED) with a central wavelength of λ = 635 nm (red) and a bandwidth of $\Delta\lambda \approx 20$ nm. An LED, as opposed to a laser, was chosen deliberately. While lasers provide superior spatial coherence, an LED's partial spatial and temporal coherence is advantageous for this experiment. It ensures a robust, non-single-photon intensity suitable for fast ensemble measurements and avoids complications associated with photon-counting statistics and non-classical light interpretations (Mandel, 1999). The source's coherence length is shorter than the path imbalance in the system, making interference contingent on correct optical alignment, thus providing a sensitive probe for visibility changes.

The beam is spatially filtered and collimated before illuminating a standard double-slit mask. The slit width a and center-to-center separation d are chosen (e.g., a = 0.1 mm, d = 0.5 mm) to produce a clear, measurable interference pattern at the detection plane located at a distance L = 1.5 m. This Young's double-slit configuration provides the canonical testbed for wave-particle duality (Feynman et al., 1965).

The key element for encoding and controlling WPI is a polarization-based tagging system. Directly behind each slit, a linear polarizer is placed. The polarizer behind slit 1 is set to transmit horizontal polarization (H), and the polarizer behind slit 2 transmits vertical polarization (V). This establishes a one-to-one correspondence between the physical path and the photon's polarization state, providing perfect potential WPI (Scully et al., 1991). The which-path information is stored not in a separate quantum system but in a degree of freedom (polarization) of the photon itself.

At the detection plane, a motorized rotational mount holds the final analysis polarizer (or a polarizing beamsplitter cube paired with two detectors). This is the crucial "choice" element. If this final polarizer is removed, or set to 45°, the H and V states are made indistinguishable with respect to the measurement basis, erasing the path information and allowing interference from the two slits to form. If the final polarizer is set to either H or V, it projects the photon onto a definite path state, destroying the interference pattern and yielding particle-like behavior (Jacques et al., 2007). The intensity distribution is recorded by a linear photodiode array or a CMOS/CCD sensor operating in analog intensity mode, providing the spatial distribution I(x) needed for statistical analysis.

Predictive Control Loop

The novel component of the Ze apparatus is the embedded predictive control loop, which realizes the continuous, adaptive regulation of predictability. The loop is implemented on a microcontroller unit (MCU), such as an Arduino or ESP32 platform, performing the following sequence in real-time:

1. **Ensemble Data Acquisition**: For a preset time window (e.g., 50 ms), the MCU reads the intensity values I_i from all active pixels/sensors of the detector array. This constitutes one ensemble measurement block, comprising the detection of a large number of photons (~10^6–10^9) without resolving individual quanta. This aligns with the ensemble interpretation central to our framework (Ballentine, 1970).

2. **Statistical Computation**: The MCU calculates the standard deviation σ_{obs} of the intensity distribution I(x) across the detection region of interest. This computation uses the standard formula:
   $\sigma_{obs} = \sqrt{(1/N) \cdot \Sigma_i (I_i - \mu)^2}$,
   where N is the number of pixels and μ is the mean intensity. This σ_{obs} serves as the real-time estimator for fringe contrast, as defined in Section 3.1.

3. **Comparison and Decision**: The computed σ_{obs} is compared against a pre-programmed threshold value θ. This threshold is derived from the target predictability. The control law is defined as follows:

   - If $\sigma_{obs} \geq \theta$, the current pattern is interpreted as having "high visibility." To test the hypothesis, the controller then issues a command to increase the predictability of WPI. This is done by commanding the servo motor to rotate the final polarizer towards either the H or V setting (e.g., increasing the angle from 45° towards 0°).

   - If $\sigma_{obs} < \theta$, the pattern has "low visibility." The controller then acts to decrease the predictability by commanding the polarizer towards the 45° setting (the information-erasing basis).

4. The adjustment step is small (e.g., 1-5 degrees), ensuring smooth, continuous control. The threshold θ is not a fixed constant but can be set as a function of a desired target

visibility or predictability parameter α from the theoretical model. The control loop effectively acts as a feedback system that seeks to stabilize the interference visibility around a setpoint defined by θ, by adaptively tuning the future information predictability.

Delayed-Choice Implementation and Causality

A critical design feature is the strict enforcement of the delayed-choice condition to preempt any causality concerns. The control loop's decision and the subsequent physical actuation of the polarizer are timed such that:

- The triggering event for the control algorithm is the detection of photons that have already passed through the double-slit and polarization tagging elements. Their path (and their tagged polarization state) is irrevocably determined.
- The control action (polarizer rotation) occurs after this passage but before the bulk of these photons (traveling at speed *c*) arrive at the final polarizer and detection plane. The polarizer's state is updated while the photons are in flight between the slits and the detector.

This is achieved by using a short, fast measurement window (Step 1) to sample an early part of the photon ensemble, processing the data within microseconds (Step 2-3), and executing the actuator command for the next wave of arriving photons. This creates a scenario where the future measurement basis for a given photon is decided based on a predictive estimate derived from its recently detected predecessors. The "choice" influences only the downstream analysis element. No signal travels backwards to affect the photon at the slits. This design is a direct physical implementation of Wheeler's delayed-choice thought experiment (Wheeler, 1978) and follows the causal timeline established in modern optical realizations (Ma et al., 2016).

Thus, the Ze apparatus operationalizes the central hypothesis. It uses real-time ensemble statistics (σ) as a proxy for visibility, feeds this into a control algorithm that maps it to a predictability setpoint, and physically adjusts the future measurement setting accordingly—all within a causally sound delayed-choice framework. This architecture allows for the direct experimental investigation of continuous, prediction-based control of quantum interference.

Key Result (Conceptual, not Empirical)

This work introduces and formalizes a novel conceptual paradigm for the control of quantum interference. The central, non-empirical result is the articulation and theoretical substantiation of the following principle: The manifestation (visibility) or suppression of quantum interference in a two-path system is governed not by the actualized fact of a which-path measurement, but by the predictable accessibility of which-path information (WPI) as estimated from an operational, ensemble-level parameter. This result reframes the ontology of wave-particle duality from a static, setup-dependent phenomenon to a dynamically tunable, information-theoretic regime.

Prediction Over Realization

In canonical quantum mechanics, as demonstrated in delayed-choice experiments, interference vanishes when a measurement actually acquires path information (Jacques et al., 2007). The result presented here shifts the locus of control one step earlier in the causal chain. We demonstrate theoretically that it is sufficient to have a highly predictable probability that such information could and will be acquired in the future to suppress interference, even if the specific realization of that measurement remains undetermined for any given particle in the ensemble. Conversely, maintaining a state of maximal unpredictability regarding future information access preserves maximal coherence.

This is formalized through the operational predictability parameter P, linked to the path distinguishability D in the Englert duality relation (Englert, 1996). In standard treatments, D is calculated from the quantum state and represents realized or realizable information. In our framework, a target distinguishability, D_{target}, is defined as a classical control parameter representing the predictability of future information access. The system's response—the observed visibility V_{obs}—continuously adheres to the complementarity inequality $V_{obs}^2 + D_{target}^2 \leq 1$, but with D_{target} acting as an independent variable set by an external predictive algorithm, not a dependent variable determined by a fixed apparatus. This decoupling of the predictability parameter from immediate physical realization is the core conceptual advance.

For instance, consider a system where the final measurement basis is chosen by a random number generator with a tunable bias α (probability for which-path measurement) and *1-α* (probability for interference measurement). The ensemble's behavior is not described by averaging the results of two separate, static experiments. Instead, for a given α, the effective density matrix of the ensemble, traced over the future control degree of freedom, exhibits off-diagonal coherence terms scaled by a factor $f(\alpha) = 2\sqrt{(\alpha(1-\alpha))}$. The resulting visibility V is proportional to $|f(\alpha)|$. Crucially, $f(\alpha)$ reaches its maximum of 1 when $\alpha = 0.5$ (maximum unpredictability) and its minimum of 0 when $\alpha = 0$ or 1 (maximum predictability). Thus, interference is controlled by the shape of the probability distribution over future events (α), not by which event actually occurs.

Equivalence to Adaptive Delayed-Choice

The proposed architecture yields behavior that is formally equivalent to a delayed-choice experiment, but with a fundamental shift in agency. In a standard delayed-choice experiment, a human experimenter or a pre-programmed random device makes a discrete, binary choice (interfere/not-interfere) after the particle's path traversal (Wheeler, 1978; Ma et al., 2016). The system's wave-like or particle-like behavior "retroactively" aligns with that choice.

In the predictive control framework, this discrete, external choice is replaced by a continuous, adaptive algorithm. The algorithm (e.g., the microcontroller in the Ze apparatus) does not make a definitive choice for each photon. Instead, it monitors a real-time statistical estimator of the current interference pattern (σ, the standard deviation of intensity) and adjusts the bias of a future random process (e.g., the orientation probability of a polarizer) to steer this estimator towards a target value. The system self-regulates into a steady state where the interference visibility is locked to a specific value by maintaining a corresponding level of predictive uncertainty about future WPI.

This adaptive loop creates a closed causal cycle that is isomorphic to delayed-choice but operates on a different logical level:

- **Standard Delayed-Choice**: Particle enters → (Path chosen) → External agent/device makes choice → Measurement → Outcome (wave or particle).
- **Predictive-Control "Delayed-Choice"**: Ensemble enters → (Paths chosen) → System's own ensemble statistics inform a control law → Control law sets predictability of future choice → Measurement under this predictable regime → Outcome (tuned visibility) → Statistics feedback to control law.

The behavior at the ensemble level is identical to what would be observed if an experimenter manually adjusted the measurement basis bias α in a series of traditional delayed-choice runs. However, the mechanism is automated and driven by the system's own emergent statistical properties, demonstrating that the conditions for wave-particle behavior can be managed by a simple feedback rule based on predictive information, without requiring an intelligent external chooser. This aligns with broader investigations into autonomous quantum machines and self-governing quantum systems (Lloyd, 2000; Dong et al., 2021).

Implications for the Interpretation of Measurement

This result carries significant implications for the quantum measurement problem. It further weakens the notion of measurement as a special, instantaneous physical act. Instead, it strengthens the information-theoretic and relational interpretations (Rovelli, 1996; Brukner & Zeilinger, 2009). What matters is not a mysterious "collapse" triggered by a macroscopic device, but the relational fact of information accessibility between the quantum system and a future measurement context, where accessibility is quantified by its predictability.

If interference can be smoothly tuned by merely adjusting how predictable a future information-gaining event is, then the sharp boundary between "measurement" and "unitary evolution" becomes operational rather than fundamental. The transition from quantum to classical statistics is seen as a continuous journey governed by increasing predictive certainty about information flows, reminiscent of the continuous decoherence induced by environmental coupling (Zurek, 2003), but here engineered through a controlled future. This perspective resonates with recent quantum foundational approaches that treat measurement as a physical process within quantum theory, such as the theory of quantum instruments and modern operational frameworks (Chiribella et al., 2008).

In conclusion, the key conceptual result of this work is the establishment of a rigorous framework where interference is controlled by prediction. It demonstrates that the complementarity principle can be expressed as a continuous trade-off managed by an informational predictability parameter. It realizes the logical structure of the delayed-choice experiment through an adaptive control loop, demystifying the role of the observer/chooser. Ultimately, it suggests that quantum behavior is not about what is, but about what can be predictably known, offering a fresh, operational lens through which to view the foundational principles of quantum mechanics.

Relation to Existing Paradigms

The predictive control framework for interference does not exist in isolation but is situated within a rich history of experimental and conceptual advances designed to probe the nature of measurement and information in quantum mechanics. It is essential to delineate precisely how this approach relates to and differs from established paradigms, namely the quantum eraser and the canonical delayed-choice experiment, to clarify its unique contribution.

Contrast with the Quantum Eraser Paradigm

The quantum eraser, introduced by Scully, Drühl, and collaborators (Scully & Drühl, 1982; Scully et al., 1991), provided a revolutionary insight: interference, once destroyed by the acquisition of which-path information (WPI), can be restored by subsequently erasing that information in a coherent manner. In a typical realization, WPI is stored in an ancillary quantum system (e.g., an atom's internal state or a photon's polarization). Interference is absent when this information is, in principle, accessible. By performing a specific measurement on the ancilla that projects it onto a superposition state orthogonal to the "which-path" basis, the path information is erased, and interference fringes reappear in a post-selected sub-ensemble correlated with that erasure measurement.

The key distinction between the quantum eraser and the predictive control (Ze) approach is one of temporal logic and operational goal.

- **Quantum Eraser**: Operates with a fixed, binary sequence: mark (store WPI) → observe (no interference) → optionally erase (restore interference for a sub-ensemble). The restoration is an a posteriori effect, visible only after correlating results with a specific erasure outcome. The overall pattern on the main detector, without this correlation, remains a featureless blob (Walborn et al., 2002). The eraser actively changes the correlations between systems to recover information that was seemingly lost.
- **Predictive Control (Ze)**: Does not employ a separate erasure step on a tagged sub-ensemble. Instead, it regulates the informational regime from the outset. The control parameter (predictability P) directly sets the effective distinguishability D_target, which continuously governs the visibility V of the entire, unconditioned ensemble in real time. There is no separation into "marked" and "erased" subsets; the entire statistical output adapts continuously. The Ze apparatus proactively manages the potential for information gain, whereas the quantum eraser reactively manipulates information already encoded.

Contrast with the Canonical Delayed-Choice Experiment

Wheeler's delayed-choice gedankenexperiment and its subsequent realizations (Wheeler, 1978; Jacques et al., 2007; Ma et al., 2016) forcefully illustrated the contextual nature of quantum reality. In these experiments, the decision to close (interference configuration) or leave open (which-path configuration) a second beamsplitter in an interferometer is made after the photon has already transited the first beamsplitter and is in flight. The result confirmed that the photon behaves as a wave or a particle in accordance with this delayed choice.

While the Ze apparatus is architecturally a delayed-choice setup (the polarizer setting is changed after path traversal), its operational philosophy and outcome differ fundamentally.

- **Canonical Delayed-Choice**: Implements a discrete switch between two mutually exclusive configurations. The experimental logic is: for a given particle, either the interference setup or the which-path setup is physically realized by the delayed choice. The outcome is a binary result: wave behavior or particle behavior. The statistics accumulate from a series of these discrete, independent choices.

- **Predictive Control (Ze)**: Does not perform discrete switching between configurations for individual photons. Instead, it continuously tunes a parameter of a probabilistic future choice, specifically the bias (α) of a random process that will select the measurement basis. The apparatus is never in a definitive "wave" or "particle" configuration for the ensemble as a whole. It is in a superposition of future configurations, weighted by a classical probability α. The measured interference visibility is a continuous function $V(\alpha)$ of this bias, representing a coherent mixture of behaviors at the ensemble level. As derived in the conceptual framework, the visibility follows $V \propto \sqrt{[\alpha(1-\alpha)]}$, a continuous curve, not a step function. This yields a smooth transition from wave-like to particle-like statistics, which is qualitatively different from the binary toggling of the classic delayed-choice.

The Ze Approach: Regulating the Informational Regime

The synthesis of these contrasts defines the novelty of the predictive control approach. It does not merely switch configurations (like a delayed-choice) or manipulate correlations (like a quantum eraser). Its core function is to regulate the informational regime in which the quantum ensemble exists.

This regime is defined by a single, classical parameter: the predictable accessibility of future information. By adjusting this parameter, one navigates the continuum described by the Englert duality relation $V^2 + D^2 \leq 1$ (Englert, 1996), not by jumping from one vertex ($V=1$, $D=0$) to another ($V=0$, $D=1$), but by smoothly tracing the connecting curve. The experimental setup is not being reconfigured; the rule governing the future extraction of information is being tuned. This transforms the apparatus from a device that enforces a specific reality into a device that enforces a specific level of predictive certainty about potential realities.

Consistency with the Standard Quantum Formalism

A critical and necessary clarification is that this novel operational approach does not modify the formalism of quantum mechanics. No new dynamics, no nonlinearities, and no collapse mechanisms beyond the standard Born rule are introduced. The entire process is describable within the framework of unitary evolution, projective measurement, and the density matrix formalism for mixed states (Nielsen & Chuang, 2010).

The system (photon paths) is entangled with a "control" degree of freedom (the future random choice device, modeled as a classical stochastic variable or a quantum system in a mixed state). The predictability parameter P (or α) defines the mixture of this control state. The reduced density matrix of the photon, obtained by tracing out the control, has its coherence terms weighted by the decoherence factor f(α). The subsequent measurement on the photon yields statistics consistent with this mixed state. The feedback loop in the Ze apparatus is a classical control system that dynamically adjusts the mixing parameter α based on the output statistics, creating a self-consistent cycle entirely within standard quantum theory. This aligns with modern operational approaches to quantum mechanics that treat preparations, transformations, and measurements as abstract elements of a theory (Hardy, 2001; Chiribella et al., 2011).

Therefore, the contribution of the Ze approach is not foundational in the sense of proposing a new theory, but methodological and interpretative. It provides a new experimental and conceptual tool—predictability as a control knob—to explore the information-theoretic boundaries of quantum phenomena. It demonstrates that the intricate dance between wave and particle, so famously highlighted by the quantum eraser and delayed-choice experiments, can be choreographed not just by decisive acts, but by the subtler, continuous control of what we can predict about the future.

Philosophical and Methodological Implications

The predictive control framework for quantum interference, as developed in the preceding sections, extends beyond a specific experimental proposal. It carries significant implications for the philosophy of quantum mechanics and the methodology of quantum experimentation, prompting a re-evaluation of core concepts such as measurement, information, and the very purpose of foundational experiments.

Measurement Re-envisioned as Management

Traditionally, in both textbook presentations and foundational discourse, measurement occupies a unique and often problematic role. It is frequently conceptualized as a passive registration or revelation of a pre-existing property, yet quantum theory itself often denies the existence of such properties prior to measurement. The infamous "collapse of the wave function" posits measurement as a singular, non-unitary interruption of the smooth unitary evolution (von Neumann, 1932).

The predictive control paradigm suggests a profound shift in perspective: measurement is most fruitfully understood not as registration, but as managed information extraction. In the Ze apparatus, the final polarizer setting (the measurement basis) is not a static, given condition. It is the output of a control loop designed to achieve a specific informational goal—maintaining a target level of predictive uncertainty. The measurement setting is engineered in response to the system's own statistical behavior. This recasts the measurement process from a mysterious, terminal event into an integral part of a dynamic feedback cycle. This view aligns with and operationalizes the relational interpretation of quantum mechanics (Rovelli, 1996), where properties are not absolute but are defined relative to another system, here, the adaptively tuned measurement device.

This framework resonates with operational approaches to physics, where the meaning of concepts is tied to procedures (Bridgman, 1927). "Wave-like behavior" is operationally defined by a high value of the statistical estimator σ under conditions of low informational predictability. There is no need to invoke an ontological wave; the behavior is a direct consequence of the managed informational relationship between the system and the apparatus. This demystifies measurement by embedding it within a control-theoretic context, similar to how feedback control is used to stabilize quantum states in quantum optics (Wiseman & Milburn, 2009).

Interference as a Consequence of Informational Openness

The second major implication concerns the origin of interference. Conventionally, interference is seen as a signature of a "wave" or of "coherence." In the predictive control view, this is refined: Interference is a statistical signature of informational openness. A system displays interference when, from the perspective of the final measurement context, its past path remains informationally ambiguous—not just unknown, but fundamentally unpredictable given the established future measurement protocol.

The continuous trade-off $V \propto \sqrt{[P(interf) * P(path)]}$ derived in our framework makes this explicit. Maximum interference (V_{max}) occurs not when a which-path measurement is simply avoided, but when the probabilities for future path and interference measurements are perfectly balanced ($P(interf) = P(path) = 0.5$). This is the point of maximal symmetry and minimal informational bias in the future. Any deviation, any increase in the predictability of one type of information over the other, symmetrically degrades the visibility. Thus, interference is not merely present or absent; it is quantified by the degree of informational symmetry or openness engineered into the future of the system.

This perspective seamlessly integrates with the decoherence program (Zurek, 2003). Decoherence describes the loss of interference through the uncontrolled dissemination of information into an environment. Predictive control describes the preservation or tuning of interference through the careful management of the predictable flow of information to a designated "future environment" (the measurement device). Both are sides of the same coin: interference is the observable remnant of restricted information flow. Our approach makes this principle an engineering tool.

From Passive Interpretation to Coherence Engineering

Historically, experiments like the double-slit, quantum eraser, and delayed-choice have served a primarily interpretative or demonstrative function. They were designed to illustrate the paradoxical or non-classical nature of quantum theory, to test the limits of certain interpretations, or to provide evidence for foundational principles like complementarity (Greenberger & Yasin, 1988; Jacques et al., 2007). The methodology was often one of passive observation under cleverly contrived conditions.

The predictive control framework initiates a transition towards a new methodological paradigm: active coherence engineering. The Ze apparatus is not merely a device to show that interference depends on information; it is a device to control interference through information. The experimenter's role shifts from a designer of static configurations to a designer of adaptive algorithms that govern information dynamics. The "knob" is no longer a physical screw on a beamsplitter but a parameter in a control law that dictates the predictability of future informational events.

This represents a maturation of quantum foundations research, aligning it with the broader goals of quantum information science. In quantum technologies, coherence is a resource to be protected, manipulated, and consumed (Baumgratz et al., 2014). The predictive control paradigm provides a foundational language and a concrete experimental archetype for this task. It demonstrates that the most counterintuitive quantum phenomena can be placed within a feedback loop, subject to classical control objectives. This bridges the conceptual gap between philosophical debates about measurement and the practical engineering of quantum systems.

Furthermore, this approach suggests new avenues for exploring the quantum-classical boundary. By treating predictability as a continuous dial, one can study how the statistics of an ensemble transition from quantum (showing interference) to classical (showing particle-like distributions) not as a binary switch, but as a smooth crossover governed by an information-theoretic parameter. This offers a more nuanced experimental probe into emergent classicality than all-or-nothing which-path measurements.

In conclusion, the philosophical and methodological implications of this work are transformative. It proposes viewing measurement as an act of informational management, reinterprets interference as a gauge of informational openness, and pioneers a shift from passive interpretation to active coherence engineering. By doing so, it not only deepens our understanding of quantum theory but also provides a powerful new conceptual toolkit for its application.

Limitations and Scope

A rigorous assessment of any novel theoretical or experimental framework requires a clear delineation of its boundaries and inherent limitations. The predictive control paradigm for interference, while offering a new perspective on the governance of quantum phenomena, is explicitly bounded in its scope. Acknowledging these limitations is not a weakness but a necessary exercise in intellectual honesty, clarifying the domain in which the framework is valid and highlighting potential avenues for future extension. The following points define the current scope of the work.

The Ensemble Regime: Beyond the Single-Photon Limit

The most significant and deliberate limitation of the present framework is that it is formulated and validated exclusively at the level of ensembles. The Ze apparatus employs an LED source and a photodetector array measuring integrated intensity, operating firmly within the classical wave optics regime of light. It does not operate in the single-photon regime, where individual quanta are resolved, and non-classical correlations can be studied (Mandel & Wolf, 1995; Grangier et al., 1986).

This choice is fundamental to the conceptual goals. The central hypothesis concerns the statistical visibility of interference, a property that is inherently an ensemble measure. The control loop relies on real-time computation of the standard deviation σ of the intensity distribution, a calculation that requires a large number of detection events within each measurement window to yield a statistically significant estimate. Single-photon experiments, while foundational for demonstrating particle-like aspects, would require a fundamentally different control architecture based on coincidence counting and post-selection, shifting the focus from continuous real-time control to discrete, a posteriori analysis (Aspect et al., 1982).

Consequently, the results and interpretations presented here are valid for ensemble statistics. They describe how the collective behavior of a large number of quanta responds to a predictive control parameter. This does not invalidate the findings but precisely defines their domain of applicability: they pertain to the operational control of quantum statistical distributions, not to the behavior of individual quantum systems. This ensemble interpretation is a legitimate and long-standing interpretation of quantum mechanics (Ballentine, 1970), and our work operates comfortably within it. The transition to single-particle control, while a fascinating future challenge, lies outside the present scope.

σ as a Phenomenological Indicator, Not a Fundamental Observable

The operational core of the control loop is the quantity σ, the standard deviation of the spatial intensity profile. It is crucial to emphasize that σ is treated as a phenomenological indicator, not as a fundamental quantum observable. It is a classical statistical measure computed from the raw data of a macroscopic detector. It serves as a convenient, real-time proxy for the fringe visibility V, which itself is a derived statistical parameter.

This usage carries specific implications. First, σ is sensitive to all sources of intensity variation, not only quantum interference. Background light, source fluctuations, and detector noise can contribute to σ. While these can be mitigated through calibration and differential measurements, the link between σ and the theoretically ideal visibility V is necessarily approximate and setup-dependent. The control law $V_{obs} \propto \sigma_{obs} / \sigma_{max}$ is a phenomenological model, the exponent γ of which must be empirically determined for a specific apparatus. The framework does not derive σ from first principles as a quantum mechanical expectation value; it adopts it as a practical, measurable signal for feedback.

Second, because σ is an ensemble-level signal, the control feedback is inherently coarse-grained. It cannot respond to or correct for fluctuations at the level of individual photon detections. The loop's bandwidth is determined by the need to accumulate sufficient statistics to compute a reliable σ. This means the framework describes steady-state or slowly varying control of interference visibility, not instantaneous wavefunction manipulation. It is a paradigm for statistical engineering, not for fine-grained quantum state steering.

Scope: Validity within Operational Quantum Mechanics

Given these limitations, the scope of this work can be precisely defined. It provides a novel operational and control-theoretic layer atop the standard formalism of quantum mechanics. Its contributions are:

1. **Conceptual**: It introduces predictable information accessibility as a continuous control parameter for quantum statistical phenomena.
2. **Methodological**: It provides a blueprint for an adaptive delayed-choice apparatus that uses ensemble statistics in a feedback loop to regulate interference.
3. **Interpretative**: It strengthens an information-theoretic, relational view of quantum behavior, where outcomes are tied to managed informational relationships rather than intrinsic properties.

The framework does not:

- Propose modifications to quantum dynamics.
- Resolve the measurement problem for individual systems.
- Make claims about the reality of wavefunctions or the moment of collapse.
- Demonstrate non-classical effects like entanglement or Bell inequality violations.

Its power lies precisely in this focused scope. By restricting itself to the ensemble domain and employing a phenomenological control variable, it avoids the deep philosophical quagmires associated with single-quantum interpretations while delivering a concrete, testable, and technologically relevant principle: the statistical manifestations of quantum theory can be placed under predictive, information-based control.

This honest delineation is a strength. It allows the work to be evaluated on its own terms—as a contribution to the methodology of quantum control and the operational understanding of complementarity. It connects the foundational concepts of the quantum eraser and delayed-choice experiments to the engineering-oriented world of quantum feedback, providing a conceptually clean bridge between these domains. Future work may seek to extend these ideas into the single-photon regime using triggered sources and high-efficiency detection, but such an extension would constitute a new research program, building upon the ensemble-level principles established here.

In summary, the predictive control framework is valid, significant, and innovative within its clearly defined scope of ensemble-level quantum statistics and operational control. Its limitations are explicitly acknowledged, framing it not as a final theory but as a purposeful and constructive step in the ongoing dialogue between quantum foundations and quantum engineering.

Outlook

The predictive control framework for quantum interference establishes a foundational principle with broad potential for extension and application. Moving beyond the proof-of-concept stage presented in this work, the outlook encompasses both the scalability of the methodology towards practical technologies and its role in fostering a deeper conceptual synthesis between disparate fields of physics and engineering.

Scalability and Technological Pathways

The principles underlying the Ze apparatus are not confined to bulk optics on an optical table. The core concept—using a real-time statistical estimator to adjust a parameter governing future information accessibility—is inherently compatible with miniaturized and integrated platforms.

A prime direction is the implementation within integrated photonic circuits. Modern silicon or silica-on-silicon photonics allows for the precise fabrication of interferometers, phase shifters, and variable beamsplitters on a chip (Pernice et al., 2012). A predictive control loop could be implemented using on-chip detectors and a dedicated microprocessor or even an application-specific integrated circuit (ASIC). The control parameter (predictability α) could tune the coupling ratio of a Mach-Zehnder interferometer's output beamsplitter via a thermo-optic or electro-optic phase shifter, acting as the delayed-choice element (Harris et al., 2014). Such a self-optimizing photonic chip could dynamically maintain optimal interference conditions for sensing or signal routing despite environmental perturbations like temperature drift or mechanical vibration, a common challenge in photonic integrated circuits.

This leads directly to applications in quantum-enhanced sensing and metrology. Quantum sensors, such as atomic interferometers or optomechanical systems, rely on the preservation of coherence to achieve sensitivities beyond the classical standard quantum limit (Giovannetti et al., 2006; Degen et al., 2017). Decoherence from environmental noise is the primary obstacle. A predictive control loop, generalized beyond which-path information, could be used to monitor a coherence witness (analogous to σ) and adaptively adjust system parameters (e.g., magnetic field shielding, laser stabilization) to maintain a target level of coherence. This transforms passive robustness into active coherence stabilization. For instance, in a atom interferometric gravimeter, a control loop could adjust the timing or phase of interrogation pulses in real-time to compensate for predicted vibrational noise, based on an inertial sensor feedforward, effectively regulating the "predictable information leakage" to the vibrational environment.

The framework also suggests novel approaches in adaptive quantum optics. Beyond stabilizing against noise, one could envision systems that dynamically reconfigure their quantum informational state for different tasks. A reconfigurable interferometer could switch between a high-visibility mode for precision phase measurement and a which-path mode for high-resolution imaging, with the transition smoothly controlled by a predictability parameter rather than a hard switch (Lloyd, 2008). This adaptability could be crucial for next-generation astronomical interferometers or lidar systems operating in turbulent environments.

Conceptual Bridge: Foundations Meets Control Theory

Perhaps the most significant long-term impact of this work lies in its potential to build a robust conceptual bridge between quantum foundations and control theory. These fields have historically evolved in parallel, with limited dialogue. Foundational experiments like the delayed-choice are celebrated for their philosophical implications but are rarely analyzed through the lens of dynamical systems or feedback. Conversely, quantum control theory often treats the quantum system as a "black box" to be manipulated, with less emphasis on the foundational meaning of the control actions themselves (Wiseman & Milburn, 2009).

The predictive control framework actively merges these perspectives.

- **It provides a foundational justification for control parameters**: The control knob is not an arbitrary voltage but is mapped directly to the predictable future information accessibility, a quantity with deep significance in quantum information theory and complementarity relations (Englert, 1996; Coles et al., 2017).
- **It recasts foundational phenomena as control objectives**: The appearance or suppression of interference is framed as a setpoint regulation problem. The wave-particle duality relation $V^2 + D^2 \leq 1$ becomes the fundamental constraint of the controlled system's state space.
- **It introduces foundational concepts into control engineering**: The idea that controlling the predictability of information flow is more fundamental than controlling the flow itself is a novel principle for designing quantum feedback protocols. It suggests that optimal control in noisy quantum environments might involve managing the statistics of information leakage rather than just compensating for its effects.

This bridge can enrich both fields. For foundational physicists, it offers a new, operational language to discuss contextuality and measurement, grounded in the concrete mathematics of transfer functions and stability criteria. For quantum control engineers, it provides a deeper, information-theoretic rationale for control strategies, potentially leading to more robust and efficient protocols inspired by fundamental principles. Preliminary theoretical work integrating predictability metrics into feedback laws shows promise in this direction.

Furthermore, this synthesis invites exploration in quantum machine learning and autonomous quantum agents. An adaptive system that controls its own quantum behavior based on predictive information is a primitive form of a quantum cognitive architecture. While highly speculative, it prompts questions about the role of prediction and feedback in the emergence of classical behavior from quantum substrates, a topic at the intersection of quantum foundations, complex systems, and artificial intelligence.

In conclusion, the outlook for the "interference controlled by prediction" paradigm is expansive. Its scalable core promises technological innovation in photonics and sensing, while its conceptual structure offers a fertile ground for unifying the abstract world of quantum foundations with the applied discipline of control theory. By demonstrating that the most enigmatic quantum behavior can be harnessed through a simple predictive feedback loop, this work points toward a future where the engineering of quantum phenomena is guided by a deep understanding of their informational nature.

Conclusion

In this work, have proposed a delayed-choice interferometric architecture in which interference visibility is regulated through predictive estimates of informational accessibility rather than through fixed experimental configurations. By introducing predictability as an operational control parameter derived from ensemble-level statistics, the scheme extends established complementarity and delayed-choice paradigms toward adaptive, information-based control of coherence.

The proposed approach does not alter the formal structure of quantum mechanics and does not invoke retrocausal dynamics or observer-dependent effects. Instead, it emphasizes the role of informational accessibility in determining whether interference manifests, consistent with information-theoretic treatments of decoherence and complementarity. The delayed-choice character of the implementation ensures that control is applied only after the system has traversed the interferometric paths, reinforcing the interpretation that interference is shaped by measurement context rather than by the system's prior history.

By framing interference as a dynamically regulated informational regime, the proposal highlights a shift from static measurement design to adaptive experimental architectures. Such a shift may be relevant not only for foundational investigations of quantum measurement, but also for practical applications where coherence must be stabilized or modulated under fluctuating informational conditions. Importantly, the experimental requirements of the scheme remain modest, allowing implementation with standard optical components and ensemble-based detection.

More broadly, the present work suggests that predictive, information-driven control can serve as a unifying perspective linking interference, complementarity, and measurement context. While the current proposal is formulated at an operational level, it opens avenues for future experimental tests and theoretical refinements aimed at exploring how informational constraints actively shape observable interference phenomena.

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