Processing Asymmetries at the Macroscopic Observer Boundary: Evidence for Observer-Dependent State Reduction

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Abstract

Two experiments test whether macroscopic biological observation is associated with a measurable temporal signature consistent with observer-dependent quantum state reduction. If biological observation constitutes a boundary condition for state reduction, biological registration should be associated with a measurable processing difference relative to comparison conditions. Across 2,675 valid trials, unobserved quantum-derived stimuli produced longer human response latencies than comparison conditions. Study 1 (parity task) showed an adjusted response-time difference of 8.68 ms (p = .0083), while Study 2 (color task) showed an adjusted response-time difference of 12.10 ms in the predicted direction (p = .0298). The effect was observed across different stimulus domains, software architectures, and response modalities. These findings provide a behavioral signature consistent with observer-dependent state reduction and provide a framework for further experimental testing.

1. Introduction

Despite the extraordinary predictive power of the quantum mechanical formalism, the ontic mechanism underlying state reduction remains intensely debated [1-2]. The standard von Neumann-Dirac formulation divides quantum evolution into two distinct processes: the deterministic, continuous, unitary evolution (Process **U**), and the discontinuous, probabilistic state reduction upon measurement (Process **R**). While the formalism has been extraordinarily successful empirically, the orthodox framework remains fundamentally ambiguous as to what physical criteria constitute a "measurement" capable of triggering this non-linear transition. For decades, theorists have proposed alternative models ranging from macroscopic universe branching [3] to non-local hidden variables [4-5] to objective spontaneous reduction frameworks [6-8]. However, a foundational line of reasoning first articulated by von Neumann [9] and Wigner [10] posits that physical matter alone cannot force Process **R**. Because a measuring apparatus interacting with an unreduced state simply becomes entangled with it, standard linear evolution generates a "von Neumann chain" of macroscopic superpositions. Resolving this chain therefore raises the question of whether an explicit state-selecting boundary condition is required, which Wigner

hypothesized to be ultimately located at the threshold of empirical registration by a human observer.

A central objection to this observer-dependent state reduction invokes environmental decoherence [11], which details how thermal and atmospheric interactions rapidly destroy observable phase coherence. However, decoherence and state reduction address fundamentally distinct physical problems. While decoherence explains environmental entanglement, suppressing off-diagonal interference terms to yield an improper statistical mixture, it provides no non-unitary mechanism for ontic state selection [12,13]. It does not explain how a single, definite classical outcome actualizes from that mixture. Consequently, under the observer-dependent state reduction framework, an unobserved quantum state rendered on a macroscopic display remains, within this framework, unresolved with respect to the biological observer until the macroscopic observer boundary is crossed.

If the observer-dependent framework is correct, this active transition should not manifest as an instantaneous point-event; rather, because the proposed transition depends on the biological actualization of a definitive macroscopic percept, its temporal resolution should be constrained by the integration dynamics of the biological apparatus. Signal construction within visual networks involves high-frequency oscillatory synchrony, including gamma-band activity in the approximately 60-100 Hz range, corresponding to cycle periods of roughly 10-16 ms [14]. Such temporally structured synchronization has been proposed as a mechanism for coordinating distributed neural activity during perceptual processing [14]. In parallel, global perceptual integration depends on rapid reciprocal interactions among distributed cortical and thalamocortical networks, with relevant feedback dynamics occurring on approximately 10-15 ms timescales [15,16]. Visual temporal integration and perceptual persistence likewise operate over short millisecond-scale intervals, with experimentally observed temporal constraints extending into the approximately 10-20 ms range [17–19]. These convergent biological timescales provide a plausible physiological basis for treating biological registration as a temporally extended Process **R** rather than assuming instantaneous registration.

This dynamic creates a fundamental processing asymmetry: while comparison information can immediately engage established neural pathways, an unobserved quantum-derived state, under the observer-dependent framework, would remain subject to the temporal requirements of biological actualization at the macroscopic observer boundary. This could produce a measurable processing delay. The present study therefore introduces a protocol to isolate this hypothesized latency across distinct cognitive and perceptual channels. The primary objective is not to establish a rigid, universal time constant, as biological integration is inherently dynamic, but to determine whether a systematic delay exists at all.

To evaluate this boundary condition empirically, human behavioral response latencies are measured during visual discrimination tasks in which stimulus generation is driven either by unobserved quantum events or by comparison conditions. Within this framework, the study tests the prediction that, if biological registration constitutes a state-selecting boundary condition, unobserved quantum states should exhibit a positive response-time

difference relative to their respective comparison conditions (such as previously observed quantum states or classically generated states). Conversely, under the null hypothesis, where state reduction occurs at the detector level prior to human observation, no processing delay would be expected.

2. Methodology and Experimental Setup

2.1 Quantum Source and Hardware Isolation

A hardware-based quantum random source was constructed to generate the stochastic sequence used to determine the experimental stimuli. Radioactive decay events were detected using a Gravity ionizing radiation detector module (SKU: SEN0463) equipped with an M4011 Geiger–Müller tube, operating at 380–450 V with a nominal sensitivity of 153.8 CPM/μSv/h. To maintain isolation from macroscopic observation prior to the designated biological registration condition, the detector assembly was housed within an opaque, light-proof enclosure, and all auditory feedback mechanisms were hardware-disabled. Detector pulses were therefore generated and recorded without providing an accessible visual or auditory representation of the individual decay events to the experimenter or participant during the unobserved condition. The detector's digital pulse output was interfaced with an Arduino microcontroller and recorded as a binary event stream. Counts accumulated during a series of predetermined acquisition windows were then used to determine the numerical stimulus presented on each trial. Because unobserved and comparison trials were randomly interleaved within the same software environment and physical hardware, condition-independent hardware and software delays were shared across conditions.

All testing procedures were conducted in accordance with the ethical principles of the Declaration of Helsinki. Prior to data collection, all participants provided written informed consent regarding the voluntary nature of the study, data anonymization, and the right to withdraw at any time. The experimental paradigm involved non-invasive, minimal-risk behavioral reaction time measurements.

2.2 Study 1: Symbolic Parity

In the first study (N = 2,014 valid trials analyzed across 30 sessions), radioactive decay events were integrated over discrete four-second temporal windows. The cumulative decay count for each interval was mapped to a single-digit integer (1-9) via a sequential modulo operation, directly translating the quantum-derived event into a visual stimulus. This integer array was then entered in the experimental runtime environment (Inquisit 7) [20] under two distinct experimental conditions.

For the unobserved quantum condition, the data transfer into the runtime script was executed under strict physical occlusion of the display monitor. The experimenter

utilized blind keystroke commands (clipboard transfer) without visual feedback, ensuring that no biological observer interacted with the data array prior to participant presentation. Conversely, for the pre-observed condition, the monitor was unobstructed, and the experimenter explicitly viewed and registered each integer during the data transfer process, thereby defining the pre-observed condition.

Each experimental session comprised 80 sequential trials wherein unobserved and pre-observed stimuli were randomly interleaved. The human participants functioned as the terminal biological observer and were unaware of the distinction between the two experimental conditions. Stimuli were presented on a standard 60-Hz display (16.67 ms frame integration time), with binary responses (Even/Odd numerical parity) recorded via the integrated hardware keyboard. To prevent rhythmic anticipatory responses, sequential trials were separated by a randomized inter-trial interval ranging from 900 to 3,000 ms.

2.3 Study 2: Color Discrimination

To test cross-paradigm replication and assess the possibility of task-specific cognitive effects, a second experimental protocol (N = 661 valid trials analyzed across 12 sessions) evaluated response times to a color discrimination task. The experiment was executed using the PsychoPy [21] software suite, interfacing directly with the quantum hardware via automated serial streaming to eliminate human intervention during stimulus generation.

In Study 2, the unobserved quantum condition was generated by real-time sampling of the Geiger–Müller tube output, which was automatically polled and parsed by the software engine immediately prior to trial presentation. To construct the comparison condition, the classical PRNG condition used pseudo-random states generated by the system's deterministic mathematical pseudo-random number generator (PRNG) algorithm. Thus, unlike Study 1, in which the comparison condition consisted of quantum-derived values that had undergone prior biological observation, Study 2 contrasted unobserved quantum-derived states with independently generated pseudo-random classical states. The experimenter performed no visual or cognitive inspection of either data stream prior to or during execution.

Each experimental session was comprised of 60 trials, evenly divided into 30 unobserved quantum trials and 30 classical PRNG trials, randomly interleaved. Inter-trial intervals consisted of a uniform dark baseline state. Stimuli consisted of full-field color displays corresponding to three discrete color states (Red, Blue, Green). Decay events were mapped to these visual parameters using a modulo-3 operation, where cumulative counts of 0, 1, and 2 corresponded to Red, Blue, and Green visual states, respectively. Upon stimulus onset, the participant functioned as the terminal biological observer, responding vocally by stating the color state. Response latency was captured via an acoustic voice-key trigger using the software's real-time audio detection array, which recorded the onset time of the verbal response.

2.4 Signal Filtering and Statistical Architecture

As noted in the preregistration protocol, an initial batch of 573 trials in Study 1 was collected prior to formal submission to verify hardware timing stability. These trials represented a minor fraction of the anticipated total data volume and were retained in the primary analysis dataset. The same filtering and statistical procedures specified in the preregistration were applied to the complete dataset, and the preregistration explicitly documents the existence and retention of these trials.

To isolate the response latency and reduce the influence of response errors, anticipatory responses, attentional lapses, and other non-target sources of variance, the prespecified exclusion criteria were applied to the raw data stream. The initial trial of each experimental condition within every session was discarded to account for system stabilization and participant readiness. Trials containing incorrect parity or color responses were excluded, as were responses falling outside a 250–1,000 ms response window [22,23]

To capture trial-level dynamics across participants, reaction times were analyzed using a linear mixed-effects model (LMM) [24]. Statistical modeling was conducted in *jamovi* (Version 2.5) [25] using the GAMLj module [26], which estimates LMMs via the underlying *lme4* R package engine [27]. Experimental condition (pre-observed quantum vs. unobserved quantum in Study 1; classical PRNG vs. unobserved quantum in Study 2) was entered as a fixed effect, while the participant (N = 3) and experimental session were modeled as random intercepts to account for baseline variability across the repeated-measures structure. Models were estimated utilizing restricted maximum likelihood (REML) with the Satterthwaite approximation for degrees of freedom [28].

3. Results

3.1 Response Latency in Symbolic Parity (Study 1)

Following application of the signal filtering criteria, the final analysis included 2,014 valid responses across three participants. There were 159 incorrect parity responses in the pre-observed condition and 148 in the unobserved condition; these trials were excluded according to the prespecified criteria. The mean response latency for the pre-observed quantum condition was 439.90 ms (SD = 99.22, n = 1,002). In contrast, unobserved quantum states produced a mean response latency of 448.17 ms (SD= 108.86, n = 1,012), yielding a raw descriptive differential of 8.27 ms.

The linear mixed-effects model indicated a statistically significant condition effect. Unobserved quantum stimuli produced a systematic response latency delay relative to the comparison condition (B = +8.68 ms, SE = 3.62 ms, t(1,984.99) = 2.40, p one-tailed = .0083, 95% CI [1.58, 15.78]). The raw descriptive differential was 8.27 ms, while the mixed-effects model estimated an adjusted response time difference of +8.68 ms after accounting for participant and session variability. Random-effects estimates indicated baseline variability

between participants (SD = 78.95 ms) and session-to-session variability (SD = 22.61 ms), with a residual standard deviation of 81.12 ms. The fixed effect accounted for 0.14% of the variance (R^2 marginal = .0014), while the full conditional model accounted for 50.68% (R^2 conditional = .5068).

A sensitivity analysis evaluating stimulus integer interaction (1–9) revealed no interaction between experimental condition and specific stimulus identity ($\chi^2(8) = 0.64$, p = .9997). The absence of a significant interaction indicates that the observed latency difference did not vary detectably as a function of stimulus identity: the 8.68-ms condition effect was not detectably dependent on the specific numerical stimulus presented.

3.2 Response Latency in Color Discrimination (Study 2)

Following application of the signal filtering criteria, the final analysis included N = 661 valid responses across three participants and 12 sessions. The mean response latency for the classical PRNG condition was 456.89 ms (SD = 100.55, n = 332). In contrast, unobserved quantum states produced a mean response latency of 468.68 ms (SD = 110.45, n = 329), yielding a raw descriptive difference of 11.79 ms between the conditions.

The linear mixed-effects model indicated a condition effect in the predicted direction. Unobserved quantum stimuli produced a response-time difference relative to the comparison condition (B = +12.10 ms, SE = 6.41 ms, $t(652.0) = 1.89$, p one-tailed = .0298, 95% CI [−0.49, 24.68]). The raw descriptive differential was 11.79 ms, while the mixed-effects model estimated an adjusted response-time difference of +12.10 ms after accounting for participant and session variability. Random-effects estimates indicated substantial baseline variability between participants (SD = 612.91 ms) and session-to-session variability (SD = 362.40 ms), with a residual SD of 823.40 ms. The fixed effect accounted for 0.31% of the variance (R^2 marginal = .0031), while the full conditional model accounted for 42.96% (R^2 conditional = .4296).

Despite the complete replacement of software architecture (PsychoPy instead of Inquisit), stimulus domain (color instead of parity), response modality (vocal instead of keystroke), and comparison-condition construction (pre-observed quantum vs. PRNG-generated), the direction of the response-time difference (+12.10 ms) was consistent with the primary finding of Study 1 (+8.68 ms). Table 1 details the findings of both experiments side by side.

Table 1. Primary response-time results for both experiments in milliseconds.

	Study	Comparison RT	Unobserved RT	Raw Diff	LMM Diff	*SE*	*p*
1.	Parity (*N*=2,014)	439.90	448.17	+8.27	+8.68	3.62	.0083**
2.	Color (*N*=661)	456.89	468.68	+11.79	+12.10	6.41	.0298*

* $p < .05$, ** $p < .01$

3.3 Exploratory Evaluations

An exploratory, post-hoc evaluation of the data indicated that the response-time difference between conditions varied across the three colors. Specifically, trials involving blue stimuli exhibited the largest temporal divergence between the unobserved quantum and comparison conditions (+30.65 ms). A smaller latency differential was observed for green stimuli (+17.11 ms), while trials involving red stimuli demonstrated a negative shift (−17.10 ms), indicating no delay in the unobserved condition. Notably, the baseline reaction times in the classical PRNG condition were remarkably uniform across all three color states (Blue: 457.17 ms; Green: 456.74 ms; Red: 456.78 ms). Because evaluating specific spectral pathways was not part of the primary a priori preregistered model, this variation is reported purely as an exploratory observation, though it suggests the response-time difference may interact with specific stimulus-dependent sensory processing.

4. Discussion

4.1 The Result in Relation to the Null Hypothesis

The present experiments revealed a reproducible difference in human response time between unobserved quantum-derived states and their respective comparison conditions. Study 1 produced an adjusted response-time difference of +8.68 ms, and Study 2 produced an adjusted response-time difference of +12.10 ms.

Within the observer-dependent state-reduction model considered here, such a difference is compatible with the prediction that biological registration requires finite integration time. This creates a processing asymmetry. In the comparison conditions, the information did not require the biological registration of an unobserved quantum state and could therefore engage established neural pathways without the proposed additional processing step. In contrast, an unobserved quantum-derived state, under the proposed framework, remains subject to the temporal requirements of biological actualization at the macroscopic observer boundary. The biological integration required to construct a

definitive percept could therefore impose a measurable temporal cost, consistent with the present findings.

The critical null prediction follows from the alternative possibility that the quantum-derived state has already become classically definite before biological registration. If state reduction occurs when the Geiger–Müller detector registers the radioactive decay event, the unobserved quantum-derived state would already be classically definite before reaching the participant. In Study 1, both experimental conditions would therefore deliver classically definite information to the participant, despite their different observation histories. In Study 2, the unobserved quantum condition would likewise be classically definite before biological registration, making it physically equivalent in this respect to the classical comparison condition. Under this account, systematic response-time differences attributable to prior biological observation or to the quantum state remaining unresolved would not be expected.

4.2 Cross-Paradigm Replication and Classical Alternatives

A central methodological concern in millisecond-scale reaction-time experiments is the possibility of hardware or software artifacts. Within each protocol, quantum and comparison trials were randomly interleaved within the same experimental runtime and physical hardware, so processing delays associated with the display, computer, input device, and software environment were shared across conditions.

The two protocols also differed substantially in their experimental architectures. Study 1 used numerical parity judgments with manual keyboard responses within Inquisit 7, whereas Study 2 used color discrimination with vocal responses detected through an acoustic voice-key system within PsychoPy. The persistence of a positive response-time difference across these differences makes an explanation based on a single localized hardware or software artifact less compelling.

This cross-paradigm consistency does not eliminate all possible classical explanations. Reaction-time differences could arise from factors unrelated to quantum state reduction, including stimulus processing, attentional allocation, response preparation, or other procedural differences. The present experiments therefore do not establish that the observed response-time difference originates from quantum state reduction itself. Rather, they identify a temporal difference that is predicted by the observer-dependent framework and that persists across substantially different experimental implementations. A satisfactory alternative explanation should therefore account for the positive response-time difference observed across substantially different software architectures, stimulus domains, and response modalities.

4.3 Biological Registration and the Reaction-Time Difference

Several exploratory observations provide preliminary clues about factors that may influence the magnitude of the response-time difference. First, observations from the pilot experiment and the parity experiment indicated that the observed/unobserved difference diminished as participants accumulated experience with the task. Repeated performance can progressively automatize behavioral responses and reduce the amount of active processing required. This pattern is compatible with the proposed processing asymmetry: as task familiarity increases and responses become more automated, the temporal demands associated with biological registration may decrease.

Second, the color experiment showed that the response-time difference varied across stimulus states. The largest difference occurred for blue stimuli, a smaller positive difference was observed for green stimuli, whereas trials involving red stimuli showed a negative shift. These stimulus-dependent differences are notable because the visual system processes different spectral signals through partially distinct biological pathways and receptor populations. The present data do not establish the physiological basis of this pattern, but they raise the possibility that the magnitude of the response-time difference may depend on properties of the biological sensory interface through which information reaches conscious registration.

Taken together, these exploratory patterns suggest that the response-time difference may depend not simply on the quantum source, but on the interaction between the quantum-derived state and the biological system that registers it. This possibility has a direct methodological implication for future replication. If repeated exposure progressively reduces the effect through task automatization, excessively large numbers of trials per participant could attenuate the observed difference. Trial number, stimulus pathway, and cognitive demand should therefore be examined as preregistered moderators in future studies.

4.4 Limitations

Several limitations should be considered when interpreting the present findings. First, both experiments involved only three participants. Although the experiments included thousands of valid trials and multiple experimental sessions, the small number of independent participants limits generalizability and leaves open the possibility that individual differences contributed to the observed effects. Second, the observed response-time differences were relatively small, on the order of 9–12 ms, making them potentially sensitive to attention, task familiarity, fatigue, response strategy, and other sources of millisecond-scale behavioral variability. Third, the two experiments used substantially different stimulus domains, response modalities, and software architectures. This cross-paradigm consistency is a strength, but it also means that the experiments were not exact replications and that procedural differences cannot be completely excluded. Finally, response time provides an indirect behavioral measure rather than a direct measurement of quantum state reduction. The present findings therefore cannot determine when or where physical state

reduction occurs, nor can they by themselves distinguish observer-dependent state reduction from every possible alternative explanation. Larger preregistered studies involving substantially more participants, together with more direct tests of the proposed mechanism, will be necessary to determine the robustness and interpretation of the observed response-time difference.

4.5 Conclusion

The present experiments revealed a reproducible difference in human response time between unobserved quantum-derived stimuli and their respective comparison conditions. The effect was observed across two substantially different experimental paradigms, with adjusted response-time differences of +8.68 ms and +12.10 ms, respectively.

Within the observer-dependent state-reduction model, this difference is consistent with a processing asymmetry in which comparison information can engage established neural pathways without the proposed additional registration process, whereas an unobserved quantum-derived state remains subject to the temporal requirements of biological actualization at the macroscopic observer boundary, potentially contributing to a measurable temporal processing cost. By contrast, if the relevant quantum-derived state had already become classically definite when the Geiger–Müller detector registered the radioactive decay, no systematic difference based on prior biological observation would be expected. The observed difference is therefore consistent with observer-dependent state reduction. These findings establish an experimental framework for further preregistered replication and mechanistic testing of whether the macroscopic observer boundary represents a physically relevant boundary in quantum state reduction.

5. Data, Code, and Preregistration Availability

The experimental protocols, primary hypotheses, and statistical analysis plans were preregistered on the Open Science Framework (OSF) 10.17605/OSF.IO/KY7EA. The complete raw dataset, analysis scripts (Linear Mixed-Effects Models in Jamovi), and experimental presentation scripts (Inquisit 7 and PsychoPy runtime files) are publicly accessible at the same repository location: https://osf.io/3jwrm/overview.

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