Research Article

Trauma as a Dimensional Collapse of Response Space: A Quantum-Like Framework with Testable Predictions

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This paper proposes that persistent maladaptive fixation is characterised not by the presence of a pathological content but by a reduction in the effective size of an individual's response repertoire within a specific content domain, together with a loss of sensitivity to context. Under overwhelming demand, a state capable of supporting multiple context-dependent responses is projected onto a single response. What distinguishes fixation from an ordinary strong reaction is that this reduction persists after the demand ends: the state does not re-open. Fixated material is therefore treated not as an unresolved state awaiting collapse but as an already-collapsed one, and therapeutic action is reframed as the restoration of degrees of freedom rather than the removal of a stored entity.

This proposal responds to a gap. Attention-guided and somatically oriented interventions for persistent stress-related patterns are widely practiced and frequently report effects, yet the field lacks a unifying theoretical account of what such interventions would be changing. We offer one and specify how it could be shown to be wrong.

The account is expressed in the quantum-like formalism established in quantum cognition — Hilbert-space state representation, non-commuting observables, and contextual measurement — used as a modelling language for psychological state dynamics, and it engages the quantum decision theory programme where that literature bears on the argument. No physical quantum process in neural tissue is claimed or required, and entanglement-based accounts of interpersonal therapeutic action are excluded on principled grounds.

Reduced contextual sensitivity is already predicted by the existing compatibility account for extensively rehearsed material. The framework's distinctive claim is therefore not about contextual sensitivity alone but about its joint pattern with a behavioural measure of response repertoire and with autonomic complexity: fixated and merely familiar domains, indistinguishable by order effects,

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are predicted to be separable by state-dependent heart rate variability complexity, with arousal and respiration controlled. Falsification conditions are stated, and the decisive test targets this claim.

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1. Introduction

A large and heterogeneous class of interventions addresses persistent, situation-bound maladaptive response patterns through guided attention to bodily and affective experience. These approaches are widely practiced. They report effects. They share, in broad terms, a working assumption: that something which has become fixed can be made mobile again.

What they do not share is an account of what that "something" is.

The field's explanatory vocabulary is a patchwork. Some accounts posit stored energetic quantities to be released. Others invoke quantum-physical processes in ways that do not survive contact with physics. Others avoid theory altogether and rest on clinical observation. The consequence is that a class of interventions with plausible effects has remained isolated from theoretical scrutiny — not because the effects are implausible, but because the explanations offered are.

This paper attempts a different move. Its proposal is that what has become fixed is not a content but a narrowing of what the individual's state can do. Persistent maladaptive fixation, on this account, consists in a reduction of the number of responses an individual's state can support within a specific content domain (its effective response repertoire, defined in §3.2), together with the loss of that state's sensitivity to context. Under overwhelming demand, a state that could support several context-dependent responses is projected onto the one that is survival-relevant in that moment. What makes this fixation rather than an ordinary strong reaction is that the reduction persists once the demand has passed. That the reduction of repertoire and the loss of contextual sensitivity occur together is an empirical hypothesis of this paper, not a mathematical consequence of the formalism (§3.2), and that persistence is an additional assumption, not a consequence of projection (§3.4).

This inverts a familiar description. Fixated material is often characterised as unstable, unresolved, still open, and therapeutic work as bringing it to resolution. On the present account it is the reverse: fixation is not an un-collapsed state awaiting resolution but an already-collapsed state that has lost the capacity to re-open. Collapse is not the therapeutic goal; collapse is the pathology.

The characterisation is stated in a formalism with an established record in psychology and is accompanied by predictions that could show it to be wrong. Its distinctive empirical commitment is that fixated and merely familiar domains — which existing theory predicts to be indistinguishable by question-order effects — are separable by state-dependent autonomic complexity. If they are not, the framework adds nothing to what is already available and should be abandoned.

Section 2 introduces the quantum-like formalism, states why it is adopted and what that adoption does not commit us to, and situates the proposal relative to existing work. Section 3 presents the core proposal, its hypothesis and its additional assumptions. Section 4 shows its convergence with three independently developed frameworks. Section 5 addresses measurement. Section 6 states predictions and falsification conditions. Section 7 specifies minimum requirements for a test. Section 8 notes the broader theoretical context. Section 9 states limitations. Appendix A summarises the changes relative to version 1.

Scope with respect to mechanism, POVMs and quantum decision theory. Three questions raised in public review are deliberately kept within this paper's stated limits. First, the paper characterises what changes in persistent fixation; it does not explain why the collapsed state persists. Persistence is assumed (§3.4), no relaxation law, attractor structure or memory mechanism is offered, and §3.4 states what such an account would have to reproduce. Second, projective measurement is used as a simplification and the generalisation to positive operator-valued measures (POVMs) is left open (§2.3, §9). Third, the quantum decision theory (QDT) programme is engaged where it bears on the argument (§§2.1–2.6), without a reformulation in terms of its utility and attraction decomposition. The measurement paper [1] is a separate work that takes up none of these questions.

This is a contribution to theoretical psychology. No data are reported.

2. Quantum-Like Modelling in Psychology

2.1. An established programme

Over the past two decades a research programme has developed that applies the mathematical structure of quantum probability — not quantum physics — to human judgement and decision-making [2][3][4]. It is motivated by a recurrent finding: human judgements systematically violate the axioms of classical probability in ways that are lawful rather than merely noisy.

Question-order effects are the clearest case. Asking A before B yields different marginal response distributions than asking B before A. Survey methodology has long documented this and treated it as a nuisance to be controlled. The quantum-like approach treats it as structure: questions correspond to projection operators, and the operators for two questions need not commute. When they do not, order matters — not as a defect of the respondent but as a formal consequence of how a state is updated by the act of answering.

A second, independently developed line of work is the quantum decision theory (QDT) of Yukalov and Sornette [5][6][7]. It represents decisions as quantum-like measurements on states of mind in a Hilbert space, separates a classical-like utility component of behavioural probabilities from a context-dependent attraction (interference) component [8][9], and has been calibrated and tested quantitatively against experimental choice data [10][11]. Two aspects of this programme bear directly on the present paper. First, it states conditions under which interference and contextual effects should and should not arise [12]; weak or absent order effects therefore cannot by themselves be read as evidence of a state of reduced dimensionality. Second, it argues that uncertain and composite events are naturally described by generalised (positive operator-valued) measurements rather than by sharp projectors [9][13]. Both points are taken up in §2.3, §2.6 and §3.2.

2.2. Why this formalism rather than another

It is important to be clear about what does and does not follow from the existence of order effects.

Order effects alone do not favour a quantum-like account. Several classical frameworks accommodate them. Attractor dynamics can represent persistent response patterns as basins in a state space, following the tradition established by Hopfield [14] and developed for cognitive and neural modelling since (e.g. [15]). Markov models with order-dependent transition matrices generate sequence effects directly. Bayesian updating with context-sensitive likelihoods produces asymmetries between orders. Reinforcement-learning accounts with entrenched policies reproduce response persistence. Each is a serious framework and each can be fitted to order-effect data. The relation between quantum-like and classical accounts is, moreover, not one of simple opposition: within decision theory proper, QDT has been shown to augment rank-dependent expected utility and cumulative prospect theory rather than merely replace them [16].

The reason to prefer the quantum-like formalism is not descriptive elegance. It is that the formalism commits itself to a quantitative constraint that it could fail.

Wang and Busemeyer [17] derive, from the law of reciprocity within quantum probability theory, a symmetry condition on order effects that involves no free parameters. The prediction is not that order effects will occur, nor that they will be large, but that the pattern of differences across orders will satisfy a specific equality. They supported this across six studies, and subsequently across a large collection of national survey datasets [18].

This is a different epistemic situation from the classical alternatives. Attractor and Markov models can be fitted to order effects; they do not predict in advance what value the effect must take. A parameter-free equality that survives testing across many independent datasets is the kind of constraint that makes a formalism worth adopting — and would have made it worth abandoning had it failed. QDT pursues the same aim of quantitative, out-of-sample testable prediction [19].

We adopt the formalism on this basis, and on no other.

A second question must be separated from the first, since answering one does not answer the other. That the formalism has earned adoption does not establish that the present proposal requires it, and it would be misleading to imply otherwise. The predictions developed in Section 6 concern a reduction in effective response repertoire together with a reduction in contextual sensitivity, and each could be expressed in an attractor or precision-weighting vocabulary. In version 1 of this paper we argued that the quantum-like formalism supplies the link between the two, so that a state that has lost dimensionality has thereby lost contextual sensitivity. That argument does not hold in general and is withdrawn. The effective response repertoire is a property of a state in a response basis; contextual sensitivity is a property of the state and of two questions; the two are formally distinct (§3.2). The QDT literature makes the same point from another direction, by separating a utility component from a context-dependent attraction component [8] [9] and by specifying conditions under which interference does or does not arise [12]. Weak order effects can result from a state that is diagonal in the question basis, from approximate compatibility, from decoherence, or from averaging over heterogeneous respondents, none of which requires a reduced repertoire; and a state concentrated on one response can show large order effects (§3.2).

The link between reduced repertoire and reduced contextual sensitivity is therefore an empirical hypothesis (§3.3), not a consequence of the formalism. What the formalism contributes is the parameter-free constraint on which its adoption rests, a precise language in which the two quantities can be told apart, and a way of stating the hypothesis so that it can fail. The predictions of Section 6 discriminate

fixation from familiarity; they do not discriminate the quantum-like account from its classical alternatives, except through P4.

2.3. The formal apparatus

States and the Born rule. An individual's state with respect to a content domain is a density operator ρ on a Hilbert space H. A question is a set of projectors Π_i summing to the identity, $\Sigma_i \Pi_i = I$. The probability of response i is

$$p(i) = \mathrm{Tr}(\rho \Pi_i) \tag{1}$$

State update (Lüders' rule). Following a response i,

$$\rho \mapsto \rho'_i = \frac{\Pi_i \rho \Pi_i}{\mathrm{Tr}(\rho \Pi_i)} \tag{2}$$

Answering is not a passive readout. It changes the state that any subsequent question interrogates. This is the formal source of order effects. The identification of questions with measurements and of answering with state update follows the general approach of quantum cognition and of QDT [5][6].

Compatibility. Two questions A and B are compatible if their projectors are defined with respect to a common basis, incompatible otherwise. Order effects arise only for incompatible questions: if $[\Pi(A), \Pi(B)] = 0$, order is irrelevant.

Projective measurement as a simplification. The formulation uses projectors and Lüders' rule throughout. This is a simplification. Psychological questions are often uncertain, composite, or imperfectly operationalised, and QDT has argued that such cases are naturally described by positive operator-valued measures (POVMs) rather than sharp projectors [9][13]. The quantities used below — the response distribution and the order effect — are defined through outcome probabilities $p(i) = \mathrm{Tr}(\rho E_i)$ and remain meaningful for a general POVM $\{E_i\}$, with Lüders' update replaced by the corresponding Kraus-operator update. We retain the projective form for clarity and because the QQ equality on which our adoption of the formalism rests [17] is formulated in that setting. Extending the predictions to POVMs is left open (§9).

2.4. When compatibility arises: a critical distinction

Wang and Busemeyer [17] address directly when questions become compatible, and their answer is consequential.

They propose that incompatibility is expected when questions are new or unusual, such that a response must be constructed at the moment of asking. Where a respondent has extensive experience with a particular combination, they may have developed a representation permitting both to be answered from a common basis — and order effects then disappear.

This carries an implication that must be confronted rather than sidestepped. Reduced order effects are already predicted by the existing literature for material that has been extensively rehearsed. Any account proposing reduced order effects for a different reason must be able to distinguish itself from this one. Section 6 specifies how. The QDT conditions for interference [12] make the same point from the side of the formalism: whether contextual effects appear depends on the relation between the state and the question structure, not on the dimension of the state alone.

We also note the constructionist stance underlying this account: attitudes and beliefs are not stored in memory as fixed properties but constructed when required, with information retrieved for one question shaping the context of subsequent construction. This is directly relevant to a proposal that treats persistent patterns as features of a construction process rather than as stored objects.

2.5. Scope of the commitment

Nothing here requires or asserts quantum processes in neural tissue. The formalism is a probability structure. Its application stands or falls on whether human judgement exhibits the structural signatures it predicts, independently of neurophysiology. The distinction between quantum-like behavioural probabilities and physical quantum processes is also drawn explicitly in the QDT literature [20].

We state one further exclusion explicitly, because informal discussion in adjacent applied fields sometimes suggests otherwise. Quantum entanglement cannot transmit information; this is the content of the no-signalling theorem, and it is closely related to the impossibility of copying an unknown quantum state [21]. No account in which one person acts causally on another through quantum correlation is available, whether or not the formalism is otherwise applicable. Every proposal in this paper concerns the structure of an individual's own state dynamics.

2.6. Relation to existing work

Adopted. The quantum-like probability formalism of quantum cognition [2][3][4], and the QDT programme of Yukalov and Sornette, in particular its treatment of non-commuting decisions, of conditions for interference, and of uncertain events by generalised measurements.

Not claimed. That the effective size of the response repertoire determines contextual sensitivity; that projection by itself explains persistence (this requires a relaxation or attractor mechanism, which is not specified here); that projective measurement is the only adequate description of psychological questions; that the physiological measures used here index the purity or dimension of a density operator.

Distinctive. (i) The explanandum: loss of context dependence within a domain, rather than a stored content. (ii) The joint prediction that fixated and familiar domains, indistinguishable by order effects, are separable by domain-specific autonomic complexity and by a behavioural estimate of the response repertoire. (iii) Explicit falsification conditions, of which one is decisive (§6.6).

Not new. Attenuated order effects for rehearsed material [17]; the availability of attractor, Markov, Bayesian and reinforcement-learning accounts for persistent patterns; the decomposition of contextual effects into utility and attraction components in QDT [8][9].

3. Core Proposal: Dimensional Collapse of Response Space

3.1. The phenomenon to be modelled

Clinical description of persistent maladaptive patterns converges on a structural feature rarely stated as such: the response has stopped depending on the situation.

A person without such a fixation, presented with a cue in a given domain, may respond in several ways depending on what preceded it, how it was framed, what else is salient. A person with a fixation in that domain responds in one way, largely insensitive to preceding context.

This is not a matter of response intensity. Intensity varies across many conditions. What distinguishes fixation is the loss of variation as a function of context. We take this, rather than the presence of a stored pathological content, as the explanandum.

3.2. Quantities

Three quantities must be kept apart (Table 1).

Response basis. Let X be a content domain and let $B = \{|r_i\rangle\}$ be the orthonormal basis of response options that the individual can enact in X, that is, the basis defined by the projectors Π_i of a reference question about the domain. The response distribution is $p_i = \langle r_i|\rho|r_i\rangle = \mathrm{Tr}(\rho\,\Pi_i)$. The choice of B is part of

the model; for psychological domains it must be specified operationally, for example by the response categories of a reference question (§7.2).

Effective response repertoire. We define the effective size of the response repertoire as the participation ratio of the response distribution in the basis B:

$$D_{\mathrm{eff}}(\rho; B) = \frac{1}{\Sigma_i p_i^2} \tag{3}$$

It counts the response options that carry non-negligible probability: it equals 1 if and only if all probability lies on a single response, and equals d for a uniform distribution over d responses. It is a property of the state relative to a response basis, not of the state alone.

Distinction from purity. The inverse purity $1/\mathrm{Tr}(\rho^2)$ is a different quantity: it measures how mixed ρ is, independently of any basis. Since $\mathrm{Tr}(\rho^2) = \Sigma_{ij} |\rho_{ij}|^2 \geq \Sigma_i \rho_{ii}^2 = \Sigma_i p_i^2$, we have $D_{\mathrm{eff}} \geq 1/\mathrm{Tr}(\rho^2)$, with equality if and only if ρ is diagonal in B. For a pure state $1/\mathrm{Tr}(\rho^2) = 1$ whatever the response distribution, whereas D_{eff} can take any value from 1 up to the dimension of the response space. Equation (3) of version 1 wrote both expressions as equal; that identification is valid only for states diagonal in B and is not used here. The exponentiated von Neumann entropy, which v1 mentioned as an alternative, is likewise a purity-type quantity and does not serve the same purpose; it is not used.

Contextual sensitivity. For two questions A and B, contextual sensitivity is the order effect: the difference between the probability of response b to B when A has been asked (and answered) first and when B is asked first,

$$\Delta_{\mathrm{AB}}(b) = \; \left| \, \mathrm{Tr}[\Pi_b(B)(\Sigma_a \Pi_a(A) \rho \Pi_a(A) - \rho)] \, \right| \tag{4}$$

Δ_{AB} without argument denotes this quantity for the response of interest, or a suitable summary over b. $\Delta_{\mathrm{AB}} > 0$ requires $[\Pi(\mathrm{A}), \Pi(\mathrm{B})] \neq 0$ and a state ρ that is not block-diagonal with respect to the decomposition of A.

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Quantity	Definition	What it characterises	Depends on
Inverse purity	$1/\mathrm{Tr}(\rho^2)$	Mixedness of the state	ρ only (basis-independent)
Effective response repertoire	$D_{\mathrm{eff}}(\rho; B) = 1 / \Sigma_i p_i^2$	Effective number of response options carrying probability	ρ and the response basis B
Order effect (contextual sensitivity)	Δ_{AB}, Eq. (4)	Dependence of the response to B on whether A was asked first	ρ and both questions A and B

Table 1. The three quantities used in this paper.

Relation between the two. D_{eff} and Δ_{AB} are formally distinct, and neither determines the other. (i) If ρ commutes with the projectors of A, then $\Sigma_a \Pi_a(A)\, \rho\, \Pi_a(A) = \rho$ and $\Delta_{AB} = 0$ for every B, however broadly ρ is spread over responses; in particular a state that is a response eigenstate of A ($D_{\mathrm{eff}} = 1$ in the basis of A) shows no order effect with any B. (ii) Conversely, $D_{\mathrm{eff}} = 1$ in the basis of B does not imply $\Delta_{AB} = 0$: for a question A whose basis is unbiased with respect to that of B, a state prepared in a basis state of B gives $p(b \mid \text{A first}) = 1/2$ against $p(b \mid \text{B first}) = 1$, a maximal effect. (iii) States of large D_{eff} may show no order effect (a maximally mixed state, or any state diagonal in the basis of A), and mechanisms that suppress order effects — decoherence with respect to the question basis, approximate compatibility, averaging over heterogeneous respondents — do not require any reduction of D_{eff} in the response basis.

Whether fixation involves both features is therefore an empirical question. The hypothesis stated in §3.3 is that in fixated domains the state is concentrated on one response in the response basis of the domain and, in addition, is approximately compatible with the questions asked in that domain (approximately block-diagonal with respect to their decompositions), so that Δ is attenuated. The second condition is an assumption about how the collapsed state relates to the question set; it does not follow from the projection alone.

3.3. The proposal

Core hypothesis (H). Fixation in a domain F consists in a reduction of D_{eff} within F accompanied by an attenuation of contextual sensitivity Δ for questions in F. These are two measurable features of one phenomenon, and their joint occurrence is the hypothesis, not a theorem of the formalism (§3.2).

Under overwhelming demand, a state supporting multiple context-sensitive responses is projected onto the response that is survival-relevant in that moment. What distinguishes fixation from an ordinary strong response is that the reduction persists — the state does not return to its prior dimensionality when the demand ends (§3.4). The clinically striking feature, that the response no longer varies with situation, is what H describes rather than something derived from it.

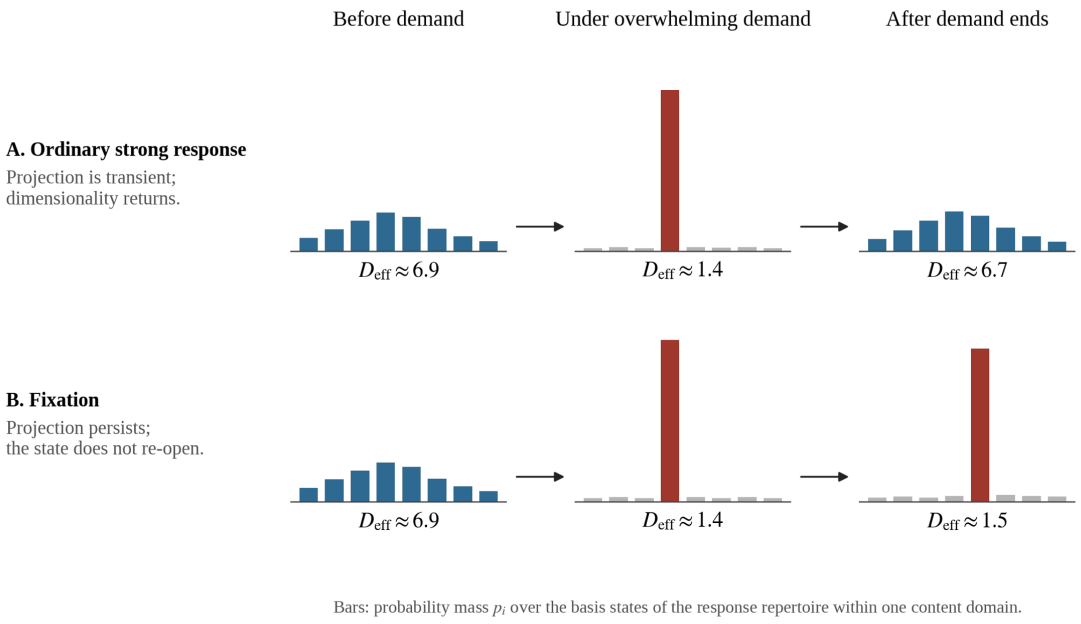


Figure 1. Dimensional collapse of response space. Bars represent the response distribution p_i over the basis states of the response repertoire within a single content domain; the D_{eff} values are the participation ratios (Eq. 3) of the plotted distributions. Both rows show the same projection under overwhelming demand; they differ in what follows it. In (A) the state re-opens and the effective response repertoire returns. In (B) it does not, and the response ceases to vary with context. The therapeutic target is the transition that fails to occur in (B), not a further collapse.

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3.4. Persistence: an additional assumption

Lüders' rule (Eq. 2) describes how a state is updated conditional on a measurement outcome. It says nothing about what happens to the state after the demand has passed. Whether the post-demand state remains near the collapsed state or relaxes back towards a broad distribution depends on the dynamics between measurements, which the update rule leaves unspecified. Persistence is therefore not derived here; it is assumed.

In dynamical terms the assumption is that the collapsed state is, for the fixated domain, approximately a slow or stable mode of the post-demand dynamics, whereas in an ordinary strong response (Fig. 1A) it is not. Candidate realisations include an attractor structure, a relaxation law with a long time constant towards the collapsed state, or construction and memory processes that reproduce the collapsed representation each time the domain is engaged (§2.4). We do not choose among these; the framework is a characterisation, not a mechanism (§9).

A mechanism, if offered in later work, would have to reproduce four features that follow from the account above and can be examined with the design of Section 7. (i) Slow recovery: reduced D_{eff} and attenuated Δ remain reduced after the demand has ended, at a delay at which an ordinary strong response has recovered. (ii) Domain specificity: recovery is impaired in the fixated domain F but not in the neutral domain N or the arousal-matched domain M. (iii) Covariation: the behavioural repertoire D_{beh}, contextual sensitivity and autonomic complexity change together over time and not independently (P1c, §6.1). (iv) Reversibility: successful intervention increases D_{eff} and Δ. These are desiderata for a mechanism, not a mechanism. Whether attractor, relaxation or construction accounts can meet them, and whether data of the kind proposed here could tell them apart, is left open.

Persistence has an operational meaning that constrains testing: reduced D_{eff} and attenuated Δ remain reduced on re-test after the demand has ended, at a delay long enough for an ordinary strong response to have recovered (§7.1). Where this is not observed, the account does not apply to the case at hand.

3.5. The inversion

It is tempting to describe such material as unstable, unresolved, "still open," and therapeutic work as bringing it to resolution. On the present account this is backwards.

Fixation is not an un-collapsed state awaiting resolution. It is an already-collapsed state that has lost the capacity to re-open.

Collapse is not the therapeutic goal; collapse is the pathology. The therapeutic target is restoration of the response repertoire (D_{eff}) and, on hypothesis H, of context-sensitivity, such that a different actualisation becomes available.

This reframes what an intervention would be doing. Not removing a stored entity, discharging an accumulated quantity, or overwriting a memory — but returning a locally rigid subsystem to a state in which more than one response is available.

3.6. What the model does not claim

1. No physical quantum process is posited in neural tissue, in cells, or between persons. The formalism is a probability structure, not a mechanism.
2. No interpersonal transmission is possible on this account (§2.5). Restoration of degrees of freedom is something an individual's own system does under conditions that make it possible.
3. Dimensionality is not a complete account. Content, meaning, developmental timing and relational context are not reducible to D_{eff}. The claim is that dimensional reduction is a structural feature common to fixations that otherwise differ, and that it is measurable. D_{eff} is not identified with the purity of the state, nor with contextual sensitivity (§3.2).
4. Projection does not by itself account for persistence (§3.4).
5. The mapping to physiology (§5) is a correspondence hypothesis, not a derivation.

4. Convergence With Established Frameworks

The proposal is not offered as a replacement for existing accounts. Its interest lies partly in the observation that independently developed frameworks describe what may be the same structural event in different vocabularies.

Memory reconsolidation. Nader, Schafe and LeDoux [22] showed that consolidated fear memories, upon reactivation, return to a labile state requiring de novo protein synthesis for restabilisation — and that this occurred whether reactivation took place one or fourteen days after conditioning, while the same treatment without reactivation left memory intact. Ecker, Ticic and Hulley [23] develop this into a clinical account of a core process of transformational change that does not depend on any particular therapeutic system or technique, illustrating it across a range of otherwise dissimilar approaches. In the present terms, the labile window is a transient increase in D_{eff}: a state that admitted one actualisation

temporarily admits others. That the window requires reactivation corresponds to the claim that a fixated pattern does not become mobile spontaneously.

Predictive processing. Accounts in this tradition [24][25] characterise persistent maladaptive patterns in terms of priors held with pathologically high precision, such that incoming evidence cannot revise them. High-precision priors and reduced D_{eff} describe closely related situations: a system whose response is determined largely independently of what the situation supplies.

Neurovisceral integration. Thayer and Lane [26] situate autonomic, attentional and affective systems within a functional network serving self-regulation and adaptability, framed explicitly in terms of dynamical systems with feedback and feedforward circuits. Of particular relevance, they characterise inhibitory processes as negative feedback permitting the interruption of ongoing behaviour and the redeployment of resources — that is, in terms of response selection — and propose that when these mechanisms are compromised, positive feedback loops may develop through disinhibition. A system that can no longer interrupt and redeploy is a system whose available responses have narrowed, and a self-reinforcing loop is one form the resulting persistence can take. Polyvagal accounts [27] describe the autonomic reaction range in related terms.

The convergence is not itself evidence. Frameworks agreeing does not establish that any is correct. What it does suggest is that the structural feature identified here is not an artefact of one theoretical vocabulary.

5. Operationalisation: Autonomic Complexity as a Proxy

5.1. The choice of measure

Heart rate variability is frequently interpreted in applied settings as an index of relaxation or recovery. Within neurovisceral integration models it carries a different meaning: an index of the regulatory capacity underlying self-regulation and adaptability [26].

The present framework requires a more specific measure still. What is at stake is not the amplitude of variation but the effective number of states the regulatory system moves among. It must be stated plainly that heart rate variability complexity measures are not measures of the purity, or of the effective dimension, of a state ρ. They characterise the temporal structure of a physiological signal; their proposed relation to D_{eff} is a correspondence hypothesis that requires independent support. Non-linear complexity

measures — sample entropy [28] among them — are closer to the quantity of interest than time-domain measures such as SDNN or RMSSD, which quantify magnitude of variation without regard to its structure. The correspondence should not be overstated: sample entropy indexes the regularity of a time series, not the number of states a system occupies, and these coincide only under assumptions that are not guaranteed to hold. Measures constructed more directly around state-space occupancy — multiscale entropy and correlation dimension — should therefore be reported alongside it, with agreement across measures treated as part of what is being tested rather than assumed. Standard definitions and recording conventions follow the Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology [29] and Shaffer and Ginsberg [30].

5.2. Two empirical precedents

Two findings support the specific measurement strategy proposed here.

First, complexity measures are state-dependent within individuals and can dissociate from other autonomic indices. Blons et al. [31] recorded HRV in participants performing a cognitive task with and without added stressors. Both vagal and entropy markers rose during the task itself in all participants; when stressors were added, entropy alone decreased, and exclusively in those participants showing an anxiety response. The authors themselves raise the question of why entropy was the only marker affected. Two qualifications are needed. The finding is a state effect under an acute stressor, not a domain-specific signature of the kind predicted here, and the extension from one to the other is an inference of this paper rather than a result of theirs. And since entropy rose during the task and fell only under added stress, complexity is not monotonically favourable; the prediction below concerns a domain-specific reduction relative to a within-session control, not high complexity as such. With those qualifications, the dissociation is a precedent for the measurement strategy proposed here.

Second, contextual autonomic measures outperform resting indices. Magnon, Dutheil and Vallet [32] found that vagal reactivity and recovery combined provided a better account of advantageous decision-making than resting vagal activity, and concluded that the widely used resting index is not the best predictor of performance. The design proposed in Section 7 accordingly measures complexity during engagement with the relevant content domain rather than at rest.

5.3. Limits of the proxy

Autonomic complexity is not a direct measurement of D_{eff}. It is a physiological correlate proposed on the argument above. Complexity measures are sensitive to respiration, posture, movement, recording length and artefact handling, all of which must be controlled rather than assumed away.

More fundamentally, a reduction in HRV complexity during engagement with a domain could arise from autonomic arousal, attentional narrowing, changes in respiration, emotional salience, or task difficulty, without any reduction of the response repertoire. Observing both reduced order effects and reduced complexity would therefore not by itself show that both reflect one underlying variable. The design in Section 7 addresses these alternatives directly — an arousal-matched comparison domain, respiration recording, and matching for task difficulty — and treats the covariation of three measures (Δ, a behavioural estimate of D_{eff}, and autonomic complexity) as the test of whether a common variable is needed (§6.1). The correspondence between a formally defined dimensionality and a physiological complexity index is a hypothesis of this paper, not a premise of it.

5.4. Companion measurement work

A separate preprint [1] develops a person-level, domain-general measurement framework for the same construct. It applies Hill numbers of order 2 to two vectors: the eigenvalue spectrum of autonomic reorganisation across a standardised multi-state protocol, and the subscale profile of an existing multidimensional coping instrument. Three differences from the present paper should be kept in view. First, it concerns the organism as a whole rather than a single content domain. Second, its physiological index characterises the geometry of reorganisation across situations, not the complexity of the signal during engagement with a domain, and its repertoire index counts strategies across a questionnaire profile, not response options within a domain under contextual framings. Third, it is stated without the quantum-like formalism and does not depend on it. Neither paper's predictions are derived from the other; whether the indices proposed there agree with the domain-specific measures proposed here is an empirical question. The synthetic analyses reported there found sample entropy noise-dominated at segment lengths of 3–5 minutes; the complexity estimation in the design of §7 should therefore use sufficiently long segments or measures suited to short recordings. Since the companion preprint was posted, its physiological index (RRI-D) has been examined in two preregistered secondary analyses of open datasets [33]. In the study whose protocol matched the framework's states (N = 41), the index was computable in all participants, was unrelated to excursion (Spearman ρ = −0.09, 95% CI −0.37 to 0.20) and

only weakly related to resting ln RMSSD (ρ = 0.21), with a bootstrap reliability of 0.71, acceptable for group comparisons but not yet for interpreting an individual's value. These results concern healthy adults and the person-level index; they neither test the domain-specific measures and predictions of Section 6 nor bear on any clinical hypothesis of this paper. One methodological finding does bear on the design of Section 7: a fixed-percentage artefact rule (successive intervals differing by more than 20%) removed respiratory sinus arrhythmia during slow breathing as though it were artefact, so recordings that include paced or slow-breathing conditions should use an adaptive artefact algorithm [33].

6. Predictions

6.1. The discrimination problem

Section 2.4 established that the existing literature already predicts attenuated order effects for extensively rehearsed material. Section 3 hypothesises attenuated order effects for fixated material. Both predict the same thing about Δ.

But the two states are clearly not the same. A person with deep familiarity in a domain has a stable, well-organised representation and remains behaviourally flexible. A person with a fixation has a rigid representation and is not. Both may have achieved a common basis — for opposite reasons. Other routes to weak order effects (§2.2) are further reasons why Δ alone cannot carry the inference.

The framework's distinctive claim is therefore not about Δ alone, but about the joint pattern of Δ, a behavioural estimate of the response repertoire, and state-dependent autonomic complexity (Table 2, Fig. 2).

Route	Order effect Δ	Behavioural D_{eff}	Complexity during engagement
Compatibility through familiarity	reduced	preserved	preserved
Compatibility through fixation	reduced	reduced	reduced
Neither (incompatible questions)	present	variable	variable

Table 2. Predicted joint pattern by route to reduced order effects.

The autonomic measure is the discriminating variable: without it the two routes to reduced Δ cannot be told apart. It is not assumed to index D_{eff}; that it does so is the correspondence hypothesis under test (§5). The behavioural estimate of D_{eff} (§7.2) provides independent evidence on whether the response repertoire has in fact narrowed. Covariation of the three measures during fixation and recovery is the pattern the framework predicts; dissociation among them counts against a single common variable. No single measure suffices alone.

The comparison is within-subject and within-session: complexity during engagement with the fixated domain versus during engagement with a matched neutral domain and with an arousal-matched domain, in the same individual. This avoids any need for assumptions about between-person differences in baseline complexity, consistent with the finding of Magnon et al. [32] that contextual measures outperform resting indices.

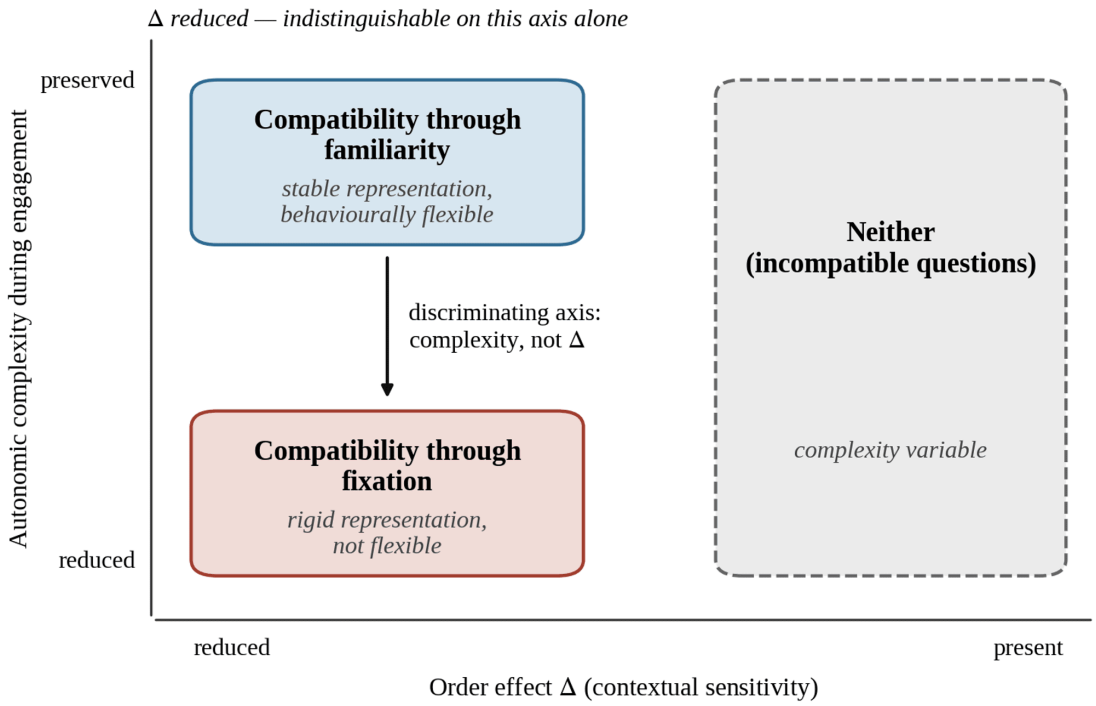


Figure 2. The discrimination plane. Familiarity and fixation both reduce the order effect and are therefore not separable along the horizontal axis. The framework's distinctive prediction is that the two occupy different regions on the vertical axis within the same individual and session, accompanied by the corresponding difference in behavioural D_{eff} (Table 2). Falsification condition 3 (§6.6): if attenuated Δ shows no systematic relationship to domain-specific complexity, the two left-hand regions do not separate and the framework adds nothing.

6.2. P1: attenuated contextuality and narrowed repertoire in the fixated domain

Prediction. In individuals with an identified fixation in domain F, order effects for unfamiliar item pairs drawn from F will be smaller than for matched unfamiliar item pairs from a neutral domain N: $\Delta_F < \Delta_N$.

Design requirement. Item pairs must be constructed to be *unusual* in both domains. Familiar combinations are predicted to show attenuated effects regardless of fixation status, eliminating the baseline against which P1 is assessed.

Statement of novelty. The direction of P1 is not novel; it is consistent with what the existing compatibility account predicts for well-rehearsed material. What is novel is the claim that the two routes are distinguishable by autonomic signature and by behavioural repertoire.

Support: $\Delta_F < \Delta_N$ reliably across participants. **Disconfirmation:** $\Delta_F \geq \Delta_N$, or no reliable difference.

P1b. Following successful intervention, Δ_F increases towards Δ_N, with Δ_N approximately unchanged as an internal specificity check.

P1c (added in this revision): behavioural response repertoire. Let D_{beh} be the participation ratio (Eq. 3) of the empirical distribution of response categories obtained when the same cues are presented under several contextual framings (§7.2). In individuals with a fixation in F, D_{beh} in F will be lower than in N, and will increase following successful intervention. **Support:** $D_{beh}(F) < D_{beh}(N)$ reliably, covarying with Δ_F across participants and over time. **Disconfirmation:** D_{beh} and Δ_F dissociate (one changes while the other does not), or D_{beh} shows no domain difference.

6.3. P2: domain-specific autonomic signature

Prediction. In individuals with a fixation in F, complexity recorded during engagement with F will be reduced relative to complexity during engagement with N and with an arousal-matched domain M, within the same session, with respiration entered as a covariate. In individuals whose attenuated Δ reflects familiarity without fixation, no such domain-specific reduction is predicted.

Prediction (intervention). Following intervention, autonomic change will appear preferentially in complexity measures rather than time-domain measures.

Why this is not obvious. Applied HRV literature emphasises increases in overall variability as the marker of improvement. The framework predicts something more specific: change in effective dimensionality, which complexity measures index more directly than amplitude. The dissociation reported by Blons et al. [31], in which entropy alone responded to added stressors, is a precedent for exactly this pattern.

Support: reliable within-subject domain difference in complexity that survives adjustment for respiration and is absent in M; larger standardised effects for complexity than time-domain measures post-intervention. **Disconfirmation:** no domain-specific complexity difference; a difference explained by arousal, respiration or task difficulty; or time-domain change with complexity flat.

6.4. P3: dissociation of timing

Prediction. Autonomic change may be detectable before self-reported change, since restored flexibility is treated as necessary but not sufficient for symptom change.

6.5. P4: the formalism must survive in the fixated domain

Prediction. The QQ equality of Wang and Busemeyer [17] is a parameter-free constraint on the pattern of order effects across the two orders. It is predicted to be satisfied in both the fixated and the neutral domain. On the present account, an attenuated order effect in the fixated domain reflects a state that is approximately compatible with the questions asked, which remains a legitimate state within the formalism — not a departure from it.

Why this matters. This is the one prediction on which the choice of formalism is itself at stake, rather than serving as a convenient vocabulary. Section 2.2 adopts quantum probability because it commits to a constraint it could fail; that argument is only fully available to the present paper if the constraint is also carried into the phenomenon the paper is about. If the QQ equality holds in the neutral domain but is systematically violated in the fixated one, the structure assumed here is not what generates order effects in fixated material, and the justification given in Section 2.2 does not transfer.

Estimation caveat. Where order effects are small in both domains, the equality is satisfied near-trivially and the test has correspondingly little power. It is informative chiefly in the neutral domain, and, following intervention, in the fixated domain as its order effects recover. We note this rather than presenting P4 as a strong test at baseline.

Support: QQ equality satisfied within estimation error in both domains. **Disconfirmation:** systematic violation confined to the fixated domain.

6.6. Falsification

The framework is disconfirmed if:

1. Symptom improvement occurs reliably without change in either Δ or autonomic complexity.
2. Δ_F exceeds Δ_N under the stated design requirements.
3. Attenuated Δ shows no systematic relationship to domain-specific autonomic complexity.
4. The domain-specific complexity difference (P2) is accounted for by arousal, respiration or task-difficulty covariates, or is equally present in the arousal-matched domain M.
5. Δ, D_{beh} and autonomic complexity dissociate systematically, so that no single common variable accounts for their changes during fixation and recovery.

Condition 3 is decisive. It targets the framework's only genuinely distinctive claim. If reduced order effects and reduced autonomic complexity are unrelated, the framework adds nothing to the existing compatibility account and should be abandoned. Condition 4 ensures that a positive result cannot simply be attributed to arousal, respiration or task difficulty.

7. How This Could Be Tested

We report no data. This section specifies minimum requirements a test would have to meet, for any intervention claiming to restore response flexibility.

7.1. Requirements

Three domains per participant. An identified fixation domain F, a matched neutral domain N, and an arousal-matched domain M — emotionally salient for the participant but not fixated. N and M serve as within-subject specificity controls: an effect confined to F is informative; an effect in F and M alike is not attributable to fixation.

Pre-specified domain identification. The procedure by which the fixated domain is identified must be fixed in advance and must not draw on the measures used to test the predictions. If a domain is selected because the participant appears rigid in it, and rigidity in that domain is then the outcome, P1 is guaranteed in part by the selection rather than by the phenomenon. An independent route is required — a structured interview conducted by an assessor blind to the hypotheses, or selection from a standardised domain inventory — and its inter-rater reliability should be reported. This paper does not specify such a procedure, and its absence is a precondition of testing rather than a detail of implementation.

Participant burden and ethical approval. Repeated engagement with a fixated domain is demanding by construction, and item batteries built to be unfamiliar within that domain may be distressing in ways familiar material would not be. A study of this kind requires ethical approval, a distress protocol, clinician availability during sessions, and explicit withdrawal provisions. The design should also record whether burden, engagement and dropout differ between the domains, since a systematic difference would confound the within-subject comparison on which both P1 and P2 rest.

Unfamiliar item pairs, as required by §6.2, piloted for unfamiliarity as well as comprehensibility.

Persistence. At least one re-test after a delay long enough for an ordinary strong response to have recovered, to assess the persistence assumption of §3.4.

Independent outcome assessment. Outcome measures must be obtained independently of the person delivering the intervention. Any measure administered and interpreted by the practitioner who performed the intervention cannot serve as evidence, since the expected result is known in advance. This constraint is stated explicitly because it is frequently violated in this literature.

Pre-registration of hypotheses, primary measures and analysis plan before data collection.

Measures. Continuous ECG-derived HRV with pre-specified artefact handling, reporting both time-domain and complexity measures; independent recording of respiration (rate and depth) and ratings of arousal and task difficulty per domain, entered as covariates; a validated symptom instrument; item-pair batteries for estimation of Δ and D_{beh}. Segment lengths must be sufficient for stable complexity estimation (§5.4).

7.2. The central methodological problem

Order effects are probability-level phenomena. A single participant answering a single item pair once yields a binary response, not a probability. Standard estimation aggregates across participants, which is incompatible with a within-subject pre/post design.

One possible resolution aggregates across item pairs within participant — multiple pairs per domain, order counterbalanced — yielding a per-participant estimate of Δ. The same route applies to D_{beh}: the same cues are presented under several contextual framings and the response categories are pooled within domain, giving an empirical response distribution whose participation ratio is D_{beh}. The response categories that define the basis B are fixed in advance by the reference question of the domain. This assumes item pairs and cues within a domain are sufficiently exchangeable to be pooled. That assumption is untested and may not hold. We identify it as the principal obstacle to testing P1b and P1c and do not claim to have solved it.

Note that P2 does not face this problem: autonomic complexity is estimated from a continuous signal within a single session and requires no aggregation across participants.

7.3. Design constraints

A within-subject pre/post design cannot separate intervention effects from regression to the mean, repeated testing, or expectancy. The comparison domains provide specificity, not control. A randomised comparison condition is required before any causal claim. Blinding of participants is not feasible for

interventions of this class. This limits what any such study can establish and should be stated rather than minimised.

8. Theoretical Context: Information-First Ontologies

The proposal above is stated entirely at the level of psychological modelling and requires nothing further. Readers who wish to may skip this section without loss. We note only that several positions in the foundations of physics treat information rather than matter as fundamental — Görnitz [34], developing von Weizsäcker's ur-theory, proposes abstract quantum bits of information free of definite meaning, termed protyposis, as a pre-structure from which both the physical and the mental were formed; D'Ariano and Faggin [35] argue from quantum information theory for a panpsychism in which quantum information is prior to quantum physics. On such views, the question of how work at the level of meaning could affect physiological state does not present the structural difficulty it presents on a substance-dualist picture. This is a remark about the coherence of a research programme. It is not evidence for any claim made above, nothing in Sections 2-7 depends on it, and the exclusion of interpersonal transmission stated in §2.5 is unaffected — the entanglement invoked by D'Ariano and Faggin concerns relations within a single experiencing system. Readers who reject these ontologies entirely lose nothing of the argument.

9. Limitations

The framework is a characterisation, not a mechanism. It says what changes, not how. This is deliberate but it is also a limitation: a structural account cannot adjudicate between candidate processes that would produce the same structural change.

Persistence is assumed, not derived (§3.4). Projection describes a conditional state change at a measurement; a relaxation law, attractor structure or memory mechanism that keeps the post-demand state near the collapsed one is not specified here. Section 3.4 lists what such a mechanism would have to reproduce; providing one is left to later work.

D_{eff} is relative to a response basis (§3.2), and the basis for a psychological domain has to be specified operationally. This paper does not fix a general procedure for doing so beyond the reference-question route of §7.2.

The link between reduced response repertoire and reduced contextual sensitivity is a hypothesis (§3.3), resting on the further assumption that the collapsed state is approximately compatible with the questions asked in the domain. It is not a consequence of the formalism, and weak order effects have several other possible sources (§2.2).

Projective measurement is a simplification (§2.3). A POVM formulation may be more appropriate for uncertain and composite psychological events, and the predictions have not been extended to it. Likewise, this paper engages the QDT programme where it bears on the argument but does not attempt a reformulation in terms of QDT's utility and attraction decomposition.

The central correspondence is hypothetical. That autonomic complexity indexes the same dimensionality as D_{eff} is proposed and tested, not established, and reduced complexity has alternative causes (§5.3).

Item exchangeability (§7.2) is unresolved. The proposed route to within-subject estimation of Δ and D_{beh} rests on an untested assumption.

Domain identification is not operationalised here, and this is a circularity risk. Determining which domain is fixated for a given individual requires a procedure this paper does not specify. The risk is not merely that such a procedure could introduce bias but that it could make P1 partly self-confirming, since a domain selected for apparent rigidity is a domain in which rigidity is then likely to be found. Section 7.1 states the requirement that follows; meeting it is a precondition of any informative test.

The familiarity/fixation contrast requires empirical support it does not yet have. The prediction that these are separable by domain-specific autonomic complexity follows from the framework, but no study has tested it directly. The precedents cited in §5.2 are suggestive, not confirmatory. This is the framework's principal empirical commitment and its principal vulnerability.

No data are reported. Everything above is a proposal.

Notes

Changes in this version. In response to public review, the effective size of the response repertoire is now defined as a participation ratio in a stated response basis and distinguished from the purity of the state; the relation between response repertoire and contextual sensitivity is stated as an empirical hypothesis rather than a formal implication; persistence is stated as an additional assumption; and the physiological correspondence is reformulated as a covariation hypothesis with explicit controls. The scope of the paper

with respect to persistence, positive operator-valued measures and quantum decision theory is now stated at the outset (§1), §3.4 sets out what a persistence mechanism would have to reproduce, and §5.4 reports preregistered tests of the companion measurement index. Appendix A lists the changes.

Appendix A. Summary of changes from version 1

The following table maps the points raised in the public review of version 1 (doi.org/10.32388/8MYYLE) to the changes made in this revision.

Review point	Change in this version	Where
1. Quantum decision theory literature missing	QDT programme (Yukalov, Sornette and co-authors) now engaged: introduced as a second established line of work, used to qualify the link between order effects and dimensionality, to motivate POVMs, and in the delimitation of adopted, claimed and novel elements.	§§2.1-2.6, References
2. Eq. (3) identifies $1/\mathrm{Tr}(\rho^2)$ with $1/\Sigma p_i^2$	Identification withdrawn. D_{eff} defined as the participation ratio in a stated response basis; inequality $D_{eff} \geq 1/\mathrm{Tr}(\rho^2)$ with the equality condition stated; purity-type quantities (inverse purity, exponentiated von Neumann entropy) not used. Figure 1 relabelled and recomputed from the plotted distributions.	§3.2, Table 1, Fig. 1
2b. Projection does not explain persistence	Persistence stated as an additional assumption with its operational meaning; candidate mechanisms named but not chosen; re-test at delay added to the design.	§3.4, §7.1, §9
3. Reduced order effects do not imply reduced dimensionality	Parsimony argument of v1 withdrawn. D_{eff} and Δ shown to be formally distinct (three cases). Link stated as empirical hypothesis H with an explicit compatibility assumption; alternative sources of weak order effects listed.	§2.2, §3.2, §3.3
4. Projective measurement insufficiently justified	Stated as a simplification; quantities defined for general POVMs; generalisation of the predictions left open and listed as a limitation.	§2.3, §9
5. HRV correspondence weaker than the formal language suggests	HRV complexity explicitly not a measure of purity or dimension of ρ; alternative causes of reduced complexity (arousal, attention, respiration, salience, difficulty) stated; arousal-matched domain M, respiration recording and task-difficulty matching added; falsification condition 4 added.	§5.1, §5.3, §6.3, §6.6, §7.1
6. More modest formulation	Central claim reformulated as covariation of behavioural contextuality, a behavioural response-repertoire measure (D_{beh}, prediction P1c) and autonomic complexity; “constitutive” wording removed; falsification condition 5 (dissociation) added.	Abstract, §6.1, §6.2, §6.6
Other	Domain symbols changed (F fixated, N neutral, M arousal-matched). Reference numbering follows order of first citation; the title of Wang et al. (2014) is	—

Review point	Change in this version	Where
	corrected. New §5.4 points to a companion measurement preprint and notes its finding on segment length for sample entropy. Additions since the review of the companion manuscript: scope statement at the end of §1; desiderata for a persistence mechanism in §3.4 and cross-reference in §9; §5.4 extended with the preregistered tests of the companion index [33] (new reference 33; former references 33 and 34 are now 34 and 35); second review acknowledged. Unchanged: core proposal and inversion, convergence (§4), precedents (§5.2), P3, P4, decisive falsification condition 3, ethical and design requirements.	

Statements and Declarations

Funding

No specific funding was received for this work.

Potential Competing Interests

The author practices and teaches in the field of attention-guided intervention methods and derives income from this activity. No specific method is evaluated or endorsed in this article. The framework proposed here is stated in terms that would apply to, and could disconfirm, any intervention of this class including the author's own.

Data Availability

No data are reported in this article.

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Use of Generative AI

An AI assistant (Claude, Anthropic) was used for drafting assistance and for identifying candidate literature, including in the preparation of this revision. All references were verified by the author against the original sources. The author is responsible for all content.

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Declarations

Funding: No specific funding was received for this work.

Potential competing interests: The author practices and teaches in the field of attention-guided intervention methods and derives income from this activity. No specific method is evaluated or endorsed in this article. The framework proposed here is stated in terms that would apply to, and could disconfirm, any intervention of this class including the author's own.