The Metabolic Landauer Principle: Learning, Deletion, and Energy in Biological Systems

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Abstract

We propose a unified framework linking information theory, thermodynamics, and human physiology. Grounded in Landauer's principle—which states that the erasure of one bit of information has an irreducible energy cost—we hypothesize that human learning and metabolism are coupled through the energetic cost of deleting uncertainty.

Learning is conceptualized as a two-step process: (i) compression of experience into efficient predictive models and (ii) erasure of obsolete representations once confidence is sufficient. Failure to perform the latter produces informational residue—"unresolved loops"—that manifest biologically as chronic energy storage, inflammation, and stress. We term this relationship the Metabolic Landauer Principle: the energy cost of deleting uncertainty is proportional to an organism's metabolic rate and confidence in its world model.

This framework predicts that emotional resolution, cognitive clarity, and physiological health are energetically and informationally linked. The paper outlines theoretical foundations, a mathematical model, and experimental pathways to validate the Metabolic Landauer Principle across cognitive, emotional, and metabolic domains.

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1 Background

1.1 The Thermodynamics of Information and the Landauer Limit

In 1961, Rolf Landauer articulated a bridge between computation and physics: the principle that erasing one bit of information incurs an irreducible energetic cost. The lower bound for erasure at temperature T is

$$E_{\min} = k_B T \ln 2. \tag{1}$$

This result reframed memory and learning as physical processes. Any logically irreversible operation—erasing a memory cell, resetting a register—dissipates energy as heat. Developments in stochastic thermodynamics and non-equilibrium information theory have confirmed the bound across colloidal particles, molecular switches, and quantum systems.

For biological systems that store, process, and erase information, the same constraint applies. Learning, consolidation, forgetting, and synaptic pruning become thermodynamic processes bounded by Landauer's principle, with experimentally measurable energetic signatures.

1.2 Learning as Compression: The Information-Theoretic View

Within Shannon information theory, learning reduces uncertainty by compressing environmental structure into predictive codes. Kolmogorov complexity frames understanding as discovering the shortest algorithm that reproduces observations. Theories such as Schmidhuber's compression progress and Friston's free-energy principle characterize intelligence as redundancy minimization and prediction-error reduction.

Compression alone is insufficient. Efficient learners must delete obsolete data, shedding representations that no longer contribute to accurate prediction. In humans, this deletion manifests as memory pruning, synaptic downscaling during sleep, and the emotional process of closure. Erasure is thermodynamically expensive and risky; energy is committed irreversibly once the system judges that the new model subsumes the old.

1.3 Confidence and the Energetics of Deletion

Computational erasure is deterministic; biological cognition must estimate confidence. The brain must trust that its compressed model adequately explains the environment before deleting redundant scaffolds. This introduces a coupling between epistemic certainty and metabolic efficiency.

Synaptic plasticity and pruning are energy-intensive, drawing on glial metabolism. REM sleep and slow-wave oscillations—associated with consolidation and forgetting—show surges in glucose consumption alongside entropy reduction. Chronic stress, trauma, and rumination correspond to failures of confident deletion: unresolved loops remain active, consuming metabolic resources without delivering predictive efficiency.

1.4 Biological Computation and the Energy–Information Nexus

Living systems behave as thermodynamic information engines that consume free energy to reduce uncertainty. Neurons are metabolically costly: the brain is roughly 2 % of body mass yet consumes 20 % of resting energy. ATP demand spikes during synaptic plasticity, and mitochondrial density tracks regions of high computation. Thus cognition is a metabolic act—a controlled energy burn to reconfigure informational states.

At the systemic level, energy budgets spanning metabolism, stress response, and immune regulation can be framed as global optimization for minimizing prediction error. Unresolved

uncertainty leads to elevated reserves (fat storage, inflammation), analogous to redundant encoding in computation: retaining multiple copies until deletion is safe.

1.5 Toward a Unified Thermodynamic Theory of Learning

Viewing learning as thermodynamically constrained compression and deletion bridges disciplines:

- **Information theory**: Learning extracts structure and reduces entropy.
- **Thermodynamics**: Erasure dissipates energy in accord with Landauer's principle.
- **Neuroscience**: Synaptic and metabolic processes instantiate these costs.
- **Psychology**: Emotional resolution corresponds to confident deletion.
- **Physiology**: Energy storage and inflammation embody deferred computation.

The human organism's metabolic and cognitive dynamics are two facets of a single physical process: converting energetic uncertainty into informational certainty.

2 Conceptual Framework: The Metabolic Landauer Principle

2.1 Definition

We define the Metabolic Landauer Principle via the energetic cost of deleting uncertainty in biological systems:

$$E_{\text{delete}} = k_B T \ln 2 \cdot f(\mathcal{U}, \mathcal{C}, \mathcal{M}), \tag{2}$$

where $\mathcal{U}$ denotes residual informational entropy, $\mathcal{C}$ is epistemic trust in the fidelity of an updated predictive model, and $\mathcal{M}$ captures available free energy. We specify

$$f(\mathcal{U}, \mathcal{C}, \mathcal{M}) = \frac{\mathcal{U}}{\mathcal{C}} \cdot g(\mathcal{M}), \tag{3}$$

so confident systems ($\mathcal{C} \gg \mathcal{U}$) delete obsolete information at lower energetic cost, while uncertain systems incur higher barriers to letting go.

2.2 Cognitive–Thermodynamic Loop

The brain–body system operates as a closed-loop thermodynamic information engine:

(i) **Perception**: Novel data increase $\mathcal{U}$.

(ii) **Learning**: Compression decreases $\mathcal{U}$ and increases $\mathcal{C}$.

(iii) **Deletion**: When $\mathcal{C}$ exceeds a threshold $\mathcal{C}_c$, energy E_{delete} is expended to erase obsolete representations.

(iv) **Metabolic Update**: Dissipated energy frees neural and metabolic capacity for new learning.

Stalled loops—due to chronic stress or ambiguity—prevent confident deletion, yielding persistent activation, elevated cortisol, and stored energy.

2.3 Energy Storage as Deferred Computation

Energy reserves function as deferred computation under high uncertainty. When deletion is unsafe, biological systems hoard energy analogously to redundant data storage. Table 1 summarizes the mapping.

Table 1: Informational states and physiological correlates.

Informational State	Physiological Correlate	Description
Unresolved loop	Chronic stress	Recurrent prediction errors; sustained cortisol
Redundant memory	Energy storage	Fat accumulation as "uncertainty buffer"
Confident compression	Homeostasis	Balanced energy allocation and predictive trust
Excessive deletion	Burnout	Overconfidence with underpreparedness

2.4 The Confidence Threshold and Deletion Barrier

We frame the deletion barrier as

$$\Delta F_{\text{delete}} = k_B T \ln 2 \cdot \frac{\mathcal{U}}{\mathcal{C}}. \tag{4}$$

Deletion proceeds when available metabolic energy $\mathcal{M}_{\text{free}}$ exceeds this barrier:

$$\mathcal{M}_{\text{free}} \geq \Delta F_{\text{delete}}. \tag{5}$$

Confidence acts analogously to a catalyst: increasing $\mathcal{C}$ lowers the barrier, enabling irreversible transformation.

2.5 Cognitive Homeostasis as Entropy–Energy Equilibrium

The organism seeks dynamic equilibrium

$$\frac{\mathrm{d}\mathcal{U}}{\mathrm{d}t} + \frac{\mathrm{d}\mathcal{M}}{\mathrm{d}t} \approx 0. \tag{6}$$

Increases in uncertainty demand metabolic expenditure; decreasing uncertainty via learning and deletion releases energy.

2.6 Systemic Integration

Across scales, the Metabolic Landauer Principle binds processes:

- **Cellular**: Autophagy and apoptosis as data deletion with heat dissipation.
- **Neural**: Synaptic pruning and memory consolidation consuming glucose.
- **Emotional**: Resolution and forgiveness modulating cortisol and energetic release.
- **Systemic**: Metabolism and immune response buffering against uncertainty.
- **Social**: Trust loops enabling distributed compression and energetic efficiency.

2.7 Implications

Key implications include:

- Emotions regulate deletion thresholds by signaling when erasure is safe.
- Learning fatigue reflects accumulated deletion costs near the Landauer's principle bound.
- Trauma and chronic stress manifest as high-entropy attractors with blocked deletion.
- Therapeutic resolution restores epistemic trust, lowering deletion barriers.
- Synthetic cognition could leverage confidence-based deletion for energetic regulation.

2.8 Conceptual Summary

Table 2 summarizes the mapping between information-theoretic expressions and biological manifestations.

Table 2: Conceptual summary of the Metabolic Landauer Principle.

Concept	Information-Theoretic Expression	Biological Expression
Learning	Compression of data	Neural encoding
Deletion	Irreversible erasure	Synaptic pruning, emotional release
Confidence	Predictive fidelity	Trust, coherence, faith
Energy	Substrate of computation	Metabolic ATP flow
Disease	Failure of safe deletion	Chronic uncertainty, energy storage

2.9 Synthesis

The Metabolic Landauer Principle unites cognitive, emotional, and metabolic processes under a single physical law: the cost of learning and the discomfort of letting go are expressions of the same thermodynamic constraint. Learning consumes energy to compress uncertainty; confident deletion dissipates energy to achieve clarity. Adaptation emerges from the oscillation between these poles.

3 Biological Correlates

This section grounds the Metabolic Landauer Principle in neurobiological, metabolic, and psychological evidence by tracing simultaneous flows of information and energy.

3.1 Neurological Level: Energy, Memory, and Deletion

Synaptic Plasticity as Physical Information Processing. Long-term potentiation and depression require ATP for protein synthesis, ion pumping, and vesicle cycling. Forming or updating memory traces constitutes energy-intensive computation. Forgetting is equally vital: synaptic pruning during sleep and rest removes redundant connections, dissipating energy consistent with Landauer's principle.

Sleep as a Global Compression–Deletion Cycle. Wakefulness increases $\mathcal{U}$ as experiences accumulate. Slow-wave sleep performs downscaling akin to compression; REM sleep supports confidence-gated erasure of emotionally charged memories. Elevated glucose metabolism during REM, despite absent sensory input, is consistent with the energetic expense of deletion.

Neural Entropy and Predictive Efficiency. EEG and MEG entropy metrics track neural complexity. Adaptive brains exhibit moderate entropy, balancing novelty encoding with coherence. Depression and PTSD show elevated or rigidly low entropy, reflecting failures to maintain the compression–deletion equilibrium predicted by the Metabolic Landauer Principle.

3.2 Endocrine and Metabolic Level: Physiology of Unresolved Loops

Cortisol as a Marker of Epistemic Stress. Cortisol mobilizes glucose in response to uncertainty. Persistent elevation signals a high $\mathcal{U}/\mathcal{C}$ ratio—a pre-deletion state where energy is readied but never released.

Insulin and Fat Storage as Deferred Computation. Low confidence drives energy hoarding in adipose tissue, analogous to caching unverified data. Safety and predictability lower the buffer, releasing energy for growth and exploration.

Inflammation as Thermodynamic Friction. Cytokines and oxidative stress accompany prolonged uncertainty. Mitochondria operate inefficiently, dissipating more heat per ATP. Resolution of uncertainty lowers markers such as C-reactive protein (CRP) and interleukin-6 (IL-6).

3.3 Psychological and Behavioral Level: Confidence, Resolution, and Flow

Rumination and Cognitive Loops. Rumination embodies an open computational loop. Repetitive replay consumes energy without compression, increasing metabolic load and stress.

Emotional Resolution as Deletion. Resolving conflicts signals that the mind has compressed discordant information into a coherent model, allowing deletion and energetic release. Therapeutic modalities can be interpreted as protocols that raise $\mathcal{C}$ above the deletion threshold.

Flow and Energetic Efficiency. Flow states represent near-equilibrium coupling of uncertainty reduction and energy consumption. Prediction errors resolve immediately, $\mathcal{C}$ stays high, and metabolic throughput is optimized. Physiological signatures include synchronized oscillations, moderate dopamine, and reduced cortisol.

3.4 Cross-Scale Coupling

Table 3: Information operations and energy signatures across scales.

Scale	Information Operation	Biological Expression	Energy Signature
Cellular	Autophagy, apoptosis	Data deletion	ATP recycling, heat release
Neural	Synaptic pruning	Compression/erasure	High glucose consumption during REM
Endocrine	Hormonal modulation	Uncertainty buffering	Cortisol/insulin dynamics
Behavioral	Decision making	Confidence calibration	Cognitive load vs. clarity
Social	Trust formation	Distributed compression	Energetic efficiency of cooperation

3.5 Integrative Summary

Neural evidence reveals energy spikes during deletion; metabolic evidence links unresolved uncertainty to stored reserves and inflammation; psychological evidence ties confidence and closure to energetic efficiency. Health and clarity appear as dual expressions of thermodynamic optimization through informational certainty.

4 Predictions and Testable Hypotheses

We translate the Metabolic Landauer Principle into empirically testable predictions linking entropy, confidence, and energy.

4.1 Prediction 1: Epistemic Confidence Reduces Metabolic Load

Hypothesis. Higher epistemic confidence reduces basal metabolic expenditure by lowering $\mathcal{U}$ and the need for redundancy buffering.

Operationalization. Independent variable: confidence measured via psychometric scales. Dependent variables: resting metabolic rate, blood glucose variability, cortisol, C-reactive protein (CRP), and heart rate variability (HRV).

Prediction. High-confidence participants display lower resting metabolic rate for equivalent cognitive load, reduced chronic cortisol and inflammatory markers, and higher HRV.

4.2 Prediction 2: Cognitive Compression Correlates with Glucose Efficiency

Hypothesis. Learning efficiency, quantified as compression ratio between input entropy and stored representation, correlates with glucose utilization efficiency.

Operationalization. Independent variable: entropy reduction via EEG/MEG or fMRI. Outcomes: FDG-PET glucose consumption, lactate accumulation, learning curves.

Prediction. Efficient learners consume less glucose per bit of uncertainty reduced, approaching the Landauer's principle limit.

4.3 Prediction 3: Emotional Resolution Releases Measurable Energy

Hypothesis. Emotional resolution triggers acute energetic shifts corresponding to confident deletion of high-entropy emotional loops.

Operationalization. Interventions such as exposure or mindfulness therapy. Measures include VO_2, heart rate, skin conductance, cortisol, adrenaline, serotonin, EEG entropy, and subjective insight.

Prediction. Resolution moments exhibit transient energy release and sustained reduction in metabolic arousal.

4.4 Prediction 4: Sleep Energy Expenditure Tracks Informational Entropy

Hypothesis. REM sleep energy expenditure scales with informational entropy accumulated during wakefulness.

Operationalization. Wakefulness entropy index versus REM-phase glucose metabolism using polysomnography and FDG-PET.

Prediction. High-novelty days produce proportionally higher REM energy consumption.

4.5 Prediction 5: Chronic Stress Represents a Stalled Deletion State

Hypothesis. Chronic stress corresponds to high $\mathcal{U}$ with suppressed $\mathcal{C}$, yielding continuous metabolic arousal without resolution.

Operationalization. Cortisol, HRV, amygdala activation, hippocampal plasticity, rumination indices.

Prediction. Chronic stress profiles match systems with high entropy and blocked erasure pathways.

4.6 Prediction 6: Flow States Approach Landauer Efficiency

Hypothesis. Flow states reflect near-optimal coupling between entropy reduction and energy consumption.

Operationalization. Skill-challenge balance tasks with EEG, metabolic, and HRV measurements plus subjective flow scales.

Prediction. Flow minimizes energy per bit of prediction error corrected and maximizes neural coherence.

4.7 Prediction 7: Social Trust Lowers Collective Energy Expenditure

Hypothesis. Trust functions as distributed confidence, reducing redundant verification and energetic cost.

Operationalization. Cooperative tasks with high- versus low-trust groups; measures include calorimetry, communication entropy, and performance efficiency.

Prediction. Trust-primed groups expend less energy per successful outcome and exhibit reduced redundancy.

4.8 Summary Table

Table 4: Predicted markers across domains.

Domain	Hypothesis	Markers	Expected Outco
Neurological	Efficient compression lowers glucose/bit	EEG entropy, FDG-PET	High learning ef
Emotional	Resolution reduces stress energy	HRV, cortisol, EEG coherence	Energy release a
Metabolic	Uncertainty correlates with fat storage	CRP, insulin, BMI	Chronic uncerta
Sleep	REM energy $\propto$ daily entropy	Polysomnography, FDG-PET	Novelty days $\rightarrow$
Social	Trust increases collective efficiency	Communication entropy, calorimetry	Low redundancy

4.9 Experimental Paradigm Design

We propose an Energy–Information Coupling Protocol (EICP):

1. Measure baseline metabolic, neural, and confidence indices.
2. Induce uncertainty via controlled novelty or challenge.
3. Facilitate compression through feedback to elevate $\mathcal{C}$.
4. Track energetic release following deletion-ready confidence.
5. Compare high- versus low-confidence cohorts.

4.10 Overarching Prediction

Across neurons, bodies, and groups, energy-use efficiency is bounded by compression capacity and confidence in deletion. Systems that learn without deleting accumulate energetic debt; systems that compress and delete with confidence achieve energetic harmony.

5 Experimental Design

We outline four complementary studies to operationalize the Metabolic Landauer Principle across sleep, emotion, cognition, and social coordination.

5.1 Study A: Sleep Deletion Study

Aim. Test whether REM energy expenditure scales with daytime informational entropy and predicts next-day metabolic relief.

Participants. $n = 48$ healthy adults (18–40).

Design. Within-subject, three counterbalanced conditions across three lab nights: high-entropy day, low-entropy day, and control. Daytime protocols manipulate novelty using probabilistic learning, sequence prediction, and open problems.

Measures. Real-time EEG for wake entropy ($\mathcal{U}_{\text{day}}$); confidence probes; polysomnography; whole-room calorimetry; optional FDG-PET subset; morning cortisol, HRV, and memory tests.

Analyses. Linear mixed models: $E_{\text{REM}} \sim 1 + \mathcal{U}_{\text{day}} + (1 \mid \text{subject})$; mediation by overnight entropy reduction; exploratory forgetting indices.

Falsification. Null relationship between daytime entropy, REM energy, and next-day relief challenges the sleep-deletion coupling.

5.2 Study B: Emotional Resolution Metabolic Study

Aim. Determine whether emotional resolution produces acute energetic release and durable stress reduction.

Participants. $n = 60$ adults with a circumscribed unresolved stressor.

Design. Randomized controlled trial comparing a targeted resolution protocol with an active control (supportive counseling).

Measures. Continuous ECG, skin conductance, respiration, indirect calorimetry, dense EEG, micro-phenomenology time-stamps, salivary cortisol, hs-CRP, continuous glucose monitoring, and sleep actigraphy.

Outcomes. Event-aligned HRV increases, skin conductance decreases, VO_2 normalization, EEG entropy decreases and coherence increases, followed by 24–48 h cortisol reduction and sleep improvement.

Falsification. Absence of acute physiological inflection points or durable differences relative to control undermines the Metabolic Landauer Principle prediction.

5.3 Study C: Cognitive Compression and Glucose Efficiency

Aim. Quantify energy per unit of informational entropy reduced during learning.

Participants. $n = 40$ healthy adults.

Design. Within-subject comparison of compressible regularities versus incompressible noise.

Measures. EEG/MEG entropy reduction ($\Delta\mathcal{U}$), FDG-PET or calibrated fNIRS plus calorimetry, learning curves, confidence calibration.

Metric. Energy-per-bit efficiency $\eta = E_{\text{block}}/\Delta\mathcal{U}$.

Prediction. Lower η for compressible structure and steeper η decline as confidence rises.

Falsification. Equivalent or worse efficiency for compressible conditions, or independence from confidence, contradicts the hypothesis.

5.4 Study D: Social Trust and Collective Energy

Aim. Test whether trust reduces redundant verification and energy expenditure in groups.

Participants. Twenty-four teams of five.

Design. Teams randomized to trust-priming versus neutral conditions before cooperative planning tasks with hidden information.

Measures. Group calorimetry or wearable proxies, hyperscanning fNIRS, communication entropy, decision accuracy and latency.

Prediction. Trust-primed groups display lower redundancy, reduced energy per decision, and higher inter-brain coherence.

Falsification. No trust-related differences after controlling for skill implies social confidence may not map to energetic efficiency.

5.5 Shared Elements

- **Power and statistics**: Medium effects detectable with $n \approx 40$–60 per study arm; simulations for precision.
- **Primary estimands**: Slopes of energy versus entropy reduction ($\partial E / \partial \Delta \mathcal{U}$) and confidence-mediated pathways.
- **Preregistration**: Hypotheses, analyses, and exclusion criteria pre-specified; tasks and code shared openly.
- **Ethics**: Minimal risk protocols with monitoring, PET limited to subsets under radiological oversight.
- **Falsifiers**: Absence of monotonic relationships among uncertainty, confidence, and energy at any scale constrains the Metabolic Landauer Principle scope.

A Appendix A: Study A IRB Protocol

A.1 Administrative Details

Title Energy Cost of Overnight Erasure: REM Expenditure vs. Daytime Informational Entropy.

Investigators Principal Investigator (PI) with co-investigators from sleep medicine, neuroimaging, and biostatistics; certified sleep technologists.

Sites University Sleep Laboratory and Metabolic Chamber Core.

Funding To be specified per grant or contract.

A.2 Summary

We assess whether mentally novel days increase brain energy use during REM sleep and whether overnight entropy reduction relates to next-day stress relief.

A.3 Aims and Hypotheses

Aim 1. Test the relationship between stage-resolved REM energy expenditure (E_{REM}) and daytime neural entropy ($\mathcal{U}_{\mathrm{day}}$). Hypothesis: higher $\mathcal{U}_{\mathrm{day}}$ predicts higher E_{REM}.

Aim 2. Determine whether overnight entropy reduction ($\Delta \mathcal{U}$) predicts lower cortisol area-under-curve (AUC) and increased HRV. Hypothesis: greater $\Delta \mathcal{U}$ improves next-day physiological markers.

Exploratory analyses evaluate targeted forgetting of distractor traces.

A.4 Design

Within-subject, counterbalanced three-night protocol (high-entropy, low-entropy, control). Sample size $n = 48$ based on mixed model power simulations.

A.5 Eligibility

Inclusion: ages 18–40, habitual sleep 6.5–9 hours, right-handed, English fluent. Exclusion: sleep disorders, psychoactive medications, uncontrolled metabolic conditions, pregnancy, metal implants (PET subset), heavy caffeine or alcohol use, shift work.

A.6 Procedures

- **Screening**: consent, sleep/medical history, Epworth Sleepiness Scale, toxicology, pregnancy test, one-week actigraphy.
- **Day protocol**: eight-hour task battery manipulating novelty with EEG, pupillometry, and confidence probes; standardized meals, no caffeine.
- **Overnight**: polysomnography, whole-room indirect calorimetry, optional FDG-PET during REM for subset ($n = 16$).
- **Morning**: HRV, salivary cortisol, memory tests for consolidation vs. distraction.

A.7 Measures and Outcomes

Primary outcomes: E_{REM} (kJ/min) and $\Delta\mathcal{U}$ (difference between day entropy and morning resting entropy). Secondary: cortisol AUC, HRV (RMSSD), sleep architecture, task performance.

A.8 Risks and Mitigation

Sleep disruption, electrode irritation, and, for PET participants, low-dose radiation. Mitigation includes flexible scheduling, hypoallergenic materials, and radiological oversight.

A.9 Benefits

No direct clinical benefit; contribution to understanding sleep, learning, and metabolism.

A.10 Confidentiality

Coded identifiers, encrypted storage, limited access, data retention for five years post-publication.

A.11 Compensation

\$75 per night plus \$50 per day session, \$150 PET supplement, \$50 completion bonus.

A.12 Statistics

Linear mixed-effects models, mediation analyses, sensitivity covariates (chronotype, prior sleep, menstrual phase), preregistered contrasts, code shared on OSF.

A.13 Withdrawal

Participation is voluntary; partial compensation pro-rated. Alternatives include non-participation.

A.14 Adverse Event Reporting

Unanticipated problems reported within five business days; data safety monitoring board not required for minimal risk.

A.15 Consent Template

Lay summary emphasizing purpose, procedures, risks, benefits, confidentiality, compensation, voluntariness, and contacts, followed by signature fields for participant and researcher.

B Appendix B: Study B Protocol and Preregistration

B.1 Administrative Details

Title Energetic Signatures of Emotional Resolution: Physiological Change at the Moment of Closure.

Investigators Clinical psychology PI, psychiatrist, neuroscientist, biostatistician, study coordinator.

Setting Psychology clinic paired with physiology monitoring suite.

B.2 Summary

We test whether resolving a specific emotional issue produces measurable, immediate shifts in physiological signals and stress hormones.

B.3 Aims and Hypotheses

Aim 1. Examine whether resolution moments coincide with HRV increases, skin conductance decreases, VO_2 normalization, and EEG entropy reductions.

Aim 2. Assess durable effects on 24–48 hour cortisol AUC and sleep relative to active control.

B.4 Design

Randomized controlled trial ($n = 60$) comparing a targeted resolution protocol (brief exposure plus cognitive reappraisal or EMDR-inspired) with supportive counseling control. Distress screening ensures suitability; inclusion ages 21–60 with a circumscribed unresolved stressor; exclusions cover acute psychiatric risk, uncontrolled medical issues, and pregnancy.

B.5 Procedures

- **Intake**: consent, clinical interview, baseline questionnaires (GAD-7, PHQ-9, PSS, PCL-5 subset), continuous glucose monitor placement, actigraphy.
- **Intervention session**: 90–120 minutes with ECG, electrodermal activity, respiration, indirect calorimetry, 64-channel EEG, micro-phenomenology prompts, salivary cortisol series, hs-CRP baseline.
- **Follow-up**: 48-hour saliva collection, sleep summary, ecological momentary assessment of intrusions, device retrieval.

B.6 Outcomes

Primary acute: change-point aligned HRV increases, electrodermal decreases, VO_2 normalization, EEG entropy decreases and coherence increases. Primary durable: reductions in cortisol AUC and improved sleep efficiency. Secondary: decreased intrusion frequency, increased self-reported relief.

B.7 Risks and Mitigation

Potential emotional distress handled by licensed clinicians with grounding techniques and referral pathways. Sensor discomfort minimized via hypoallergenic preparation. Biological sample collection limited to saliva (blood optional).

B.8 Compensation

$100 upon completion plus $25 travel stipend, pro-rated if partial.

B.9 Statistical Analysis

Bayesian change-point detection surrounding resolution timestamps, mixed-effects models with group-by-time interaction, mediation by confidence gain. Sample size powered for medium effect ($d \approx 0.6$). Data and code archived on OSF post-publication.

B.10 Consent Template

Participant-facing consent outlines purpose, procedures, risks, confidentiality, compensation, voluntary participation, and contact information, with signature blocks.

B.11 Preregistration Skeleton

- **Primary outcomes**: event-aligned physiological deltas; 24–48 hour cortisol AUC and sleep efficiency.
- **Main analyses**: group-by-time mixed models; change-point detection anchored to resolution; mediation by confidence.
- **Data handling**: preregistered inclusion/exclusion thresholds, missing-data rules, outlier management, intention-to-treat plus per-protocol reporting.
- **Sample size**: $n = 60$ detects effect sizes of $d \approx 0.6$ with power 0.8.
- **Open science**: tasks, code, and anonymized data shared upon acceptance.

C Appendix C: Shared Instruments and Pipelines

C.1 Confidence and State Scales

Three-item state confidence slider (0–100) capturing understanding, predictability, and preparedness; relief/resolution visual analogue scale; expectancy and alliance short forms (CEQ-short, WAI-SR short).

C.2 EEG Entropy and Coherence

Processing pipeline: 64-channel montage, 1–45 Hz bandpass, independent component analysis for artifacts, 4 s epochs, Lempel–Ziv complexity, multiscale entropy (embedding dimension 2, tolerance 0.15 SD), alpha (8–12 Hz) and theta (4–7 Hz) coherence across preregistered regions.

C.3 HRV and Physiological Signals

ECG sampling at $\geq$500 Hz, RMSSD as primary HRV metric, artifact correction via Kubios. Electrodermal activity decomposed into tonic and phasic elements. Indirect calorimetry captured breath-by-breath VO_2/VCO_2.

C.4 Data Security

Identifiers stored separately with encryption, access auditing, five-year retention, de-identification prior to sharing.

C.5 Adverse Event Script

Protocol for mild distress (pause, grounding), moderate/severe distress (terminate, clinician evaluation, safety planning), and IRB reporting timeline.