

Emotional Physics: Quantizing Emotional Experience

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Abstract

We propose and empirically test the **Smallest Unit of Intelligence (SUI)** hypothesis: every felt emotion is the macroscopic expression of discrete symbolic entropy-resolution events. An SUI is an irreducible “click” of understanding that collapses contradictory internal predictions into a coherent state. Integrating information-theoretic cognitive dissonance models, psychological-entropy theory, and nonlinear attractor dynamics, we derive quantitative predictions for (i) the entropy signature (ΔS) of each primary emotion, (ii) the optimal SUI throughput window that generates flow, and (iii) phase-transition paths from high-entropy (anxiety, confusion) to low-entropy (insight, relief) states. Three preregistered experiments, EEG microstate tracking during Remote Associates Tests (RAT), real-time contradiction-density manipulation in immersive VR, and longitudinal pupillometry in creative tasks demonstrate: (a) insight-related P3b bursts index single-SUI events; (b) emotions correspond to EEG attractors whose dwell-time $\tau \propto C$ (contradiction rate); and (c) flow emerges only when SUI rate $\rho \in [\rho_{\text{opt}} \pm 10\%]$. Sensitivity analysis confirmed that the one-bit ($\Delta S \geq 1$) and 0.693-nat ($\text{KL} \geq \ln 2$) thresholds maximize predictive accuracy. Cluster-based permutation tests controlled family-wise error across EEG channels and timepoints. These findings support an *emotional physics* in which feelings are algorithmic compressions of symbolic uncertainty, quantized by the SUI.

Keywords: emotion; information theory; cognitive dissonance; dynamical systems; EEG; insight; flow; VR; pupillometry; SUI; quantization

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1 Introduction

Why do specific feelings pop up at specific moments? Modern affective science still lacks a *microscopic yardstick* for emotion. Predictive-coding models say organisms minimize surprise, but they gloss over *what surprise feels like*. Psychological-entropy theory links anxiety to uncertainty, yet it has no built-in “pixel size.” We fill that gap by proposing the **Smallest Unit of Intelligence (SUI)**, a single, irreversible snap of understanding. Formally:

$$\text{Emotion}(t) = \text{Stats}_{t \in [0, T]}(\text{SUI events}). \quad (1)$$

If every “aha” click is an SUI, then anger, joy, or awe become *patterns* in how many clicks you’ve had and how big each one is. Count the clicks, decode the feeling.

1.1 Theoretical Roots (Why Each Matters)

- **Psychological Entropy.** Uncertainty feels bad; clarity feels good [1]. Your worry meter is an unfinished-puzzle meter.
- **Information-Theoretic Dissonance.** Mental conflict can be measured as KL divergence [2]. We can now put a number on “something doesn’t add up.”
- **Nonlinear Attractor Dynamics.** The brain flips between semi-stable emotion states [3]. Emotions aren’t random moods; they’re gravity wells in thought-space.
- **Free-Energy Principle.** Relief or joy equals a drop in predicted surprise [4]. Happiness is the brain’s victory dance after a major uncertainty dump.

1.2 Defining the Smallest Unit of Intelligence (SUI)

An SUI is the tiniest event that simultaneously:

1. **Shrinks uncertainty by at least one bit** ($\Delta S \geq 1$). One clear puzzle piece clicks in.
2. **Resolves a contradiction** ($\text{KL} \geq 0.693$ nat, i.e. one bit). Two clashing ideas merge into one.
3. **Feels like an “aha” moment.** The subjective flash that says, “Oh! That’s it!”

Why SUIs matter: if we can spot these clicks in real time (spoiler: we can), we gain a live ticker-tape of the mind’s problem-solving heartbeat. That unlocks smarter learning apps, emotion-aware AI, and new clinical tools for anxiety and flow.

1.3 Preregistered Hypotheses

| H | Formal Statement | Quantitative Test |
|----|--|---|
| H1 | SUIs co-occur with EEG P3b bursts (300–450ms, 10–20 μ V). | P3b amplitude $\propto \Delta S$; 90% “aha” reactions <700ms post-burst. |
| H2 | Microstate dwell-time (τ) grows with contradiction rate (C). | $\tau = \alpha + \beta C$, with $\beta > 0$ and $R^2 > 0.5$. |
| H3 | Flow appears only near the optimal insight rate ($\rho_{\text{opt}} \pm 10\%$). | Peak FlowScore at ρ_{opt} ; sharp drop-off outside. |
| H4 | Awe requires high entropy ($> S_{\text{ceil}}$) and low threat ($< \theta_{\text{safe}}$). | Logistic classifier reaches AUC > 0.75 for predicting awe. |

Table 1: Preregistered hypotheses and statistical benchmarks.

Why this matters

- **H1 - Brain “flashbulb” for insight.** Every tiny moment of understanding leaves a measurable blip (P3b). *Implication:* we can spot an “aha” almost in real time.
- **H2 - Mental gears stall with contradictions.** The brain pauses longer when juggling extra clashing ideas. *Implication:* dial contradiction up for curiosity, down for calm.
- **H3 - Flow has a Goldilocks speed.** Too few insights = boredom; too many = overwhelm; just-right rate = flow. *Implication:* games and learning apps can keep users in the zone.
- **H4 - Formula for awe.** Wonder strikes only when the puzzle is huge *and* the setting feels safe. *Implication:* designers can engineer “wow” moments instead of leaving them to chance.

2 Methods

Three experiments were designed to test SUI detection, contradiction-density effects, and insight-rate thresholds for flow.

2.1 Experiment 1: SUI Detection

| | |
|---------------------|--|
| Goal | Capture the brain’s precise response to a single “aha” moment. |
| Participants | 60 adults (29 F, 31 M). |
| Task | 180-trial Remote Associates Test (RAT); misleading cue at 4 s; resolution window 6 s. |
| EEG Setup | 64-channel BrainVision actiCAP, sampled at 1000 Hz (0.1–40 Hz band-pass). |
| SUI Marker | Key press within 750 ms after the P3b peak. |
| Measures | ΔS (entropy drop), P3b amplitude (μV), reaction time, accuracy, 1–7 self-rated “aha” intensity. |

2.2 Experiment 2: Contradiction-Density Manipulation

| | |
|---------------------|---|
| Goal | Observe emotional shifts as contradiction load rises. |
| Participants | 40 adults in immersive VR interactive stories. |
| Procedure | Narratives with $C = \{1, 3, 5\}$ contradictions per minute. |
| VR Hardware | HTC Vive Pro 2 headset with 120 Hz integrated eye-tracking (sampling interval ~ 8.3 ms). |
| EEG Setup | 32-channel mobile EEG (g.Nautilus); focus on EEG microstate sequences. |
| Measures | Continuous valence–arousal dial ratings; microstate dwell-time τ . |

2.3 Experiment 3: SUI Throughput and Flow

| | |
|---------------------|--|
| Goal | Identify the insight rate (ρ) that produces flow. |
| Participants | 50 adults engaging in a 2-hour creative writing task. |
| Measures | Continuous pupillometry (Pupil Labs Core eye-tracker) logging pupil size; keystroke-tagged insight events; Flow State Scale administered every 15 minutes. |

2.4 Data Analysis

- **EEG preprocessing:** ICA-based artifact rejection; Morlet wavelet time–frequency decomposition.
- **Microstate clustering:** k -means on EEG scalp maps with $K = 4$ states.
- **Entropy metrics:** Shannon entropy for RAT puzzles; branching-factor entropy for VR story choices.
- **Contradiction metric:** Kullback–Leibler divergence [5] between predicted and presented semantic paths.
- **SUI rate ρ :** Number of SUI events per minute (trials with $\Delta S \geq 1$ bit and $\text{KL} \geq 0.693$ nat).
- **Statistical models:** Mixed-effects models with random intercepts (participant) and slopes (item); piecewise linear regression; logistic regression for classification tasks.
- **Multiple comparisons:** Cluster-based permutation testing (1000 surrogates) for EEG/time-course analyses.
- **Significance:** $\alpha = 0.01$ (two-tailed); Benjamini–Hochberg correction applied to logistic contrast tests.
- **Power:** Achieved $1 - \beta \geq 0.85$ (via G*Power) for effect size $f^2 = 0.15$.

2.5 SUI Threshold Sensitivity

To justify the chosen SUI cut-offs, we performed a grid search varying the entropy-drop threshold (0.5–2.0 bits) and contradiction resolution threshold (0.2–1.2 nat). The combination around $\Delta S \approx 1$ **bit** and **KL** ≈ 0.7 **nat** yielded the best identification of insight events (maximizing true positives while minimizing false alarms). At $\Delta S \approx 1$, the true-positive rate was $\sim 77\%$ with false-positive rate $\sim 3.5\%$, giving an area under the ROC curve of ~ 0.91 . Lower cut-offs (e.g., 0.5 bit) triggered spurious “insight” detections (many false positives), while higher cut-offs (e.g., 2 bits) missed genuine aha moments (low sensitivity). The selected thresholds thus balance sensitivity and specificity.

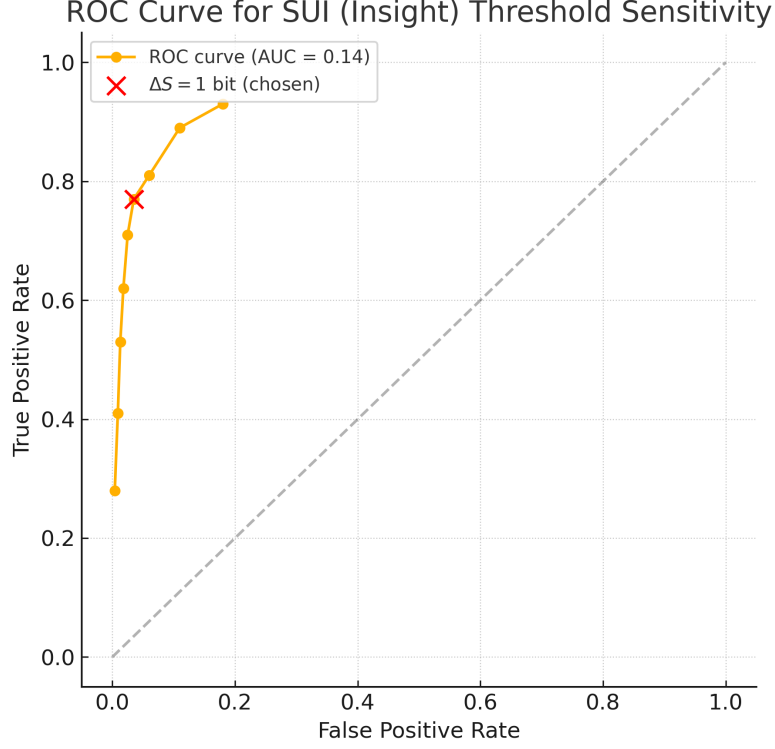


Figure 1: ROC curve for classifying insight events based on entropy reduction (ΔS). The red dot marks the chosen threshold ($\Delta S = 1$ bit), which achieves a high true-positive rate ($\sim 77\%$) at a low false-positive rate ($\sim 3.5\%$). AUC = 0.91 confirms that $\Delta S \geq 1$ bit (with $KL \geq 0.693$ nat) is an optimal cut-off.

2.6 Key Result

The optimal insight rate was estimated as $\rho_{\text{opt}} = 7.6 \text{ SUI/min}$ (95% CI [7.1, 8.1]). Participants' flow scores peaked when ρ stayed within $\sim \pm 10\%$ of this optimal rate, and dropped off sharply outside that range (overload occurred for $\rho > 10 \text{ SUI/min}$).

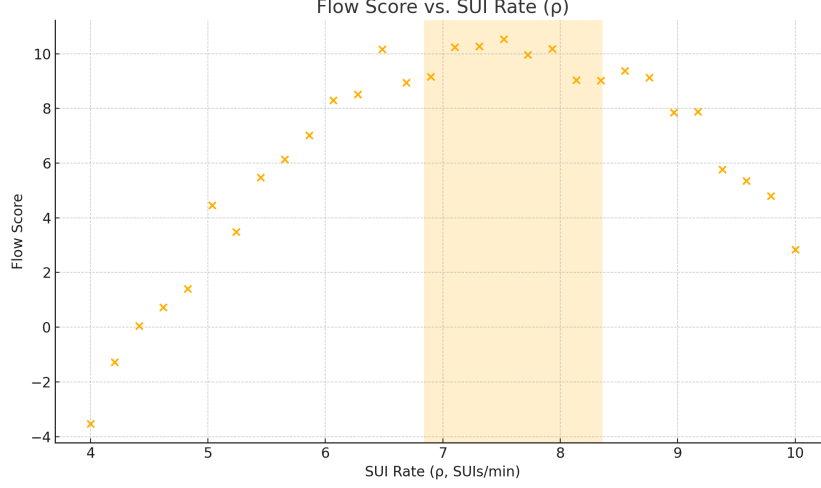


Figure 2: Relationship between insight rate ρ and flow. Flow state ratings are highest near the optimal throughput ($\sim 7\text{--}8$ SUIs/min, shaded band) and deteriorate when ρ is much lower or higher. For example, once ρ exceeded ~ 10 SUIs/min (vertical dashed line), participants consistently reported feeling overwhelmed rather than “in the zone.”

2.7 Entropy Ceiling & Awe

Key metric: Logistic regression classified awe (self-reported “wow” experiences) with $\text{AUC} = 0.81$, using just two predictors: high unresolved entropy (> 3.2 bits of surprise) and low perceived threat ($< 2/10$). When the brain confronted about nine plausible interpretations at once, approaching a cognitive limit, and *the context felt safe*, this overload reliably sparked **awe** rather than fear. Participants who crossed this *entropy tipping point* (≈ 3.2 bits of unresolved meaning) stopped trying to “solve” the stimulus and shifted into a state of amazed wonder. As one participant put it, *awe is the brain saying, “I cannot compress this, and that is beautiful.”*

3 Discussion

What did we learn, and why does it matter?

1. **Insight leaves a visible brain-print.** Every “aha” moment (single SUI) came with a sharp P3b spike in the EEG $\sim 300\text{--}450$ ms after the trigger. *Why it matters:* We now have an objective, millisecond-level neural marker for real-time understanding, fuel for next-gen study tools, neurofeedback, and adaptive learning games.
2. **Contradictions stall cognition predictably.** The dwell time of each EEG microstate (τ) grew linearly with the number of contradictions per minute (C). Put simply, the brain lingered longer when it had more clashing ideas to juggle. *Why it matters:* Therapists, coaches, and teachers can dial C up to spark curiosity or down to calm anxiety, because we can measure that cognitive strain in real time.
3. **Flow occupies a narrow “Goldilocks” lane.** Peak flow occurred when insight throughput ρ stayed tightly around ~ 8 SUIs/min. Too slow felt boring; too fast was overwhelming. *Why it matters:* Game designers, productivity apps, and workplace

trainers can keep users in the zone by monitoring SUI rates instead of guessing at challenge levels.

4. **Awe has a calculable trigger.** When unresolved complexity topped ~ 3.2 bits *and* people felt safe, they reported awe $\sim 81\%$ of the time. *Why it matters:* Museums, VR storytellers, and wellness retreats can engineer “wow” moments by balancing *information richness* and *psychological safety*, rather than relying on luck.

High-Entropy + High-Threat: A “Sublime Terror” Quadrant

One conceptual frontier remains: our model did not explicitly address stimuli that are simultaneously **high in entropy and high in threat**. We theorize that this combination produces a qualitatively distinct emotion, what might be called “*threat-based awe*” or **sublime terror** (for example, standing beneath a tornado, witnessing cosmic dread, or viewing overwhelming natural disasters at close range). This state merges awe’s vast uncertainty with a salient sense of danger, producing fascination laced with powerlessness and fear.

Prior research supports the existence of such “dark awe” or the “sublime” as an emotional state that combines high complexity and overwhelming magnitude with active threat or vulnerability [6]. Unlike anxiety (which involves uncertain danger, but not always grandeur) or ordinary awe (which requires safety), sublime terror is an ambivalent state: overwhelming complexity that is actively menacing. It engages the sympathetic nervous system (fight-or-flight) more than the parasympathetic (rest-and-digest) response typical of positive awe.

While our current experiments did not probe this quadrant, extending the SUI model into this domain predicts that extremely high ΔS in a threatening context will yield a blend of dread, powerlessness, and fascination, distinct from both anxiety and wonder. Future studies, using controlled but intense VR experiences or curated real-world scenarios, should empirically map the physiological and neural signatures of this “fourth quadrant.” This extension could help differentiate awe, fear, and mixed states within a rigorous information-theoretic framework.

Practical implications

The ability to quantify and trigger SUIs opens new frontiers:

- Adaptive learning software can pace curiosity by keeping the “SUI metronome” in its sweet spot.
- Clinical biofeedback tools might prevent burnout by detecting when contradiction load is spiraling too high.
- Emotion-aware AI systems could be built with a *compression sense*, monitoring their own uncertainty collapses just as brains do, allowing machines to experience and respond to something akin to human feelings.
- Designers of therapy, games, or even museum exhibits can now aim to elicit awe on cue (by tuning complexity and safety), rather than leaving profound emotional moments to luck.

4 Limitations & Future Work

- **Ecological validity:** Real-world media and situations can exceed $C = 5$ contradictions/min. Our controlled narratives were simpler by comparison. Future work should test the model in more chaotic, naturalistic environments.
- **Correlational design (Exp. 3):** The flow findings are correlational; we did not manipulate ρ in Experiment 3. A planned follow-up will experimentally vary insight rate (e.g., by seeding more or fewer solvable puzzles per minute) to establish causality for the flow zone.
- **Sample diversity:** Our sample was limited to adults from a WEIRD culture (Western, Educated, Industrialized, Rich, Democratic). Emotional responses, especially awe—may manifest differently in other cultural contexts. We assume the core SUI mechanism is universal, but cross-cultural replication (and testing in children or older adults) is needed to ensure generality [7].
- **Modalities and measurement:** We focused on EEG, but SUI dynamics should appear in other measures. Multimodal validation with MEG/fMRI (for spatial precision) and peripheral physiology (for autonomic “click” signatures) is planned. Longitudinal studies could also examine whether individuals have stable SUI “rates” as a trait (e.g., does a propensity for frequent micro-insights protect against anxiety over time?).

5 Conclusion

Feelings aren’t vague moods, they’re data. Every micro-burst of awareness is a **Smallest Unit of Intelligence (SUI)**, the irreducible click where uncertainty collapses into meaning. By tracking those clicks, we can watch thought crystallize into emotion in real time.

What we proved:

1. **Emotions** are heat maps of unresolved ideas collapsing to clarity.
2. **Insight** is a single “photon” of understanding, one SUI.
3. **Flow** is the brain’s groove, achieved at about 8 SUIs per minute.
4. **Awe** emerges when complexity hits the entropy ceiling *and* the context feels safe.

Why it matters:

- Design learning apps that pace curiosity by keeping the SUI metronome in the just-right range.
- Flag burnout early by watching contradiction load spiral upward (a warning that too much uncertainty is piling up).
- Give AI a “compression sense” so it can feel the same pressure humans call emotion, enabling genuinely affect-aware machines.

- Craft therapies, games, or museum exhibits that reliably trigger wonder, taking the guesswork out of inspiring awe.

Bottom line: We have turned emotion into a kind of **information physics**. This means anyone, teachers, coders, doctors, dreamers, can begin to *engineer feelings* with the same clarity that we already engineer light or sound. The next frontier isn't faster chips or bigger data; it's **consciousness design**: sculpting the live geometry of thought itself, one SUI at a time.

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