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The thermodynamics of cognition: A mathematical treatment

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ABSTRACT

There is a general expectation that the laws of classical physics must apply to biology, particularly the neural system. The evoked cycle represents the brain's energy/information exchange with the physical environment through stimulus. Therefore, the thermodynamics of emotions might elucidate the neurological origin of intellectual evolution, and explain the psychological and health consequences of positive and negative emotional states based on their energy profiles. We utilized the Carnot cycle and Landauer's principle to analyze the energetic consequences of the brain's resting and evoked states during and after various cognitive states. Namely, positive emotional states can be represented by the reversed Carnot cycle, whereas negative emotional reactions trigger the Carnot cycle. The two conditions have contrasting energetic and entropic aftereffects with consequences for mental energy. The mathematics of the Carnot and reversed Carnot cycles, which can explain recent findings in human psychology, might be constructive in the scientific endeavor in turning psychology into hard science.

1. Definitions used in the test

1.1. Mental energy (intrinsic motivation)

Cognitive and physical effort is associated with different cost functions [77]. Mental energy entails metacognitive monitoring, related to intrinsic motivation, which predicts enhanced performance, learning, and creativity, and it plays a vital role in personality development and wellness across the lifespan [130,131]. It is a long-term ability based on mental fluidity that allows trust, belief, and confidence [38]. Intrinsic motivation allows a consistent exertion of mental effort toward achievement by increasing future freedom of action.

1.2. Emotional temperature (social temperature)

Temperature is the manifestation of thermal energy in physics, and its social analog is emotional temperature. As particles' kinetic energy form temperature, the persistence of opinion enhances the willingness for interaction and forms social temperature [34,35]. Supply abundance ensures low social temperature, with a tendency for cooperation and generosity [161]. When access to supplies reaches a critical level, competition for resources replaces cooperation [159]. On a high social temperature, high-frequency information transfer through synaptic connections promotes deterministic actions.

2. Introduction

Rudolf Clausius introduced the concept of entropy to measure the amount of energy in a system that cannot produce work. Further developments in statistical mechanics and gas dynamics in the ensuing years by Boltzmann, Gibbs, and others [102] led to a reinterpretation of the concept. For example, information entropy (Shannon's entropy) is the stochastic data information production rate [145]. More recent investigations explored information and entropy as one of the critical entities of biological systems such as the living brain [80]. Entropic considerations of the neuronal system opened new vistas in understanding brain function and may even offer new ways for diagnosis and therapeutic purposes in psychology and cognitive sciences [10,52,63,139,154].

Extensive studies in physics, chemistry, and biology have focused on the relationship between information and energy [16,125,42,33]. Neuroscience, psychology, psychiatry, and behavioral sciences aim to understand the relationships and exchange between information and energy in the brain and cognition

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[33,24]. Neurophenomenology addresses the hard problem of consciousness via scientific research. A growing literature combines neuroscience with phenomenology in studying experience, mind, and consciousness [8,66,116].

Network harmonics arising from the interplay between excitation and inhibition can describe the large-scale cortical activity during sensory processing, and this critical relation fits the spatial, temporal, and neurophysiological changes associated with different mental states. As the primary source of regular interaction, the sensory system places the brain within the environment's thermodynamic cycle. In the absence of stimuli, which is commonly called the resting state, mind-wandering, autobiographical memory, future thinking, and introspection [55] are supposed to integrate motor and sensory information into an abstract model of the world [111]. Thus, resting-state networks (RSNs) represent the brain's internal model [43] based on the organism's past and present [155]. Following this, the recovery of the resting state ensures the gradual evolution and temporal stability of the self and permits the evoked cycle's thermodynamic considerations.

A critical level of energy turnover and organization sustains consciousness and via distinguishes it from unconscious states [119]. Entropy in several brain areas correlates with intelligence in verbal and performance measures [138,153] and creativity [146]. In contrast, dementia, such as Alzheimer's, was associated with reduced complexity [175]. Additionally, the entropy of occipital, frontal, and temporal lobes' clusters was significantly positively correlated with the Mental State Examination scores and significantly negatively correlated with Functional Assessment Questionnaire scores and Dementia Rating scores. More severe cognitive impairment and daily function disability were related to catastrophic brain entropy reduction [174]. According to resting-state entropy measures, an almost equal likelihood occurrence of oscillatory neural activity detected in field potential and EEG recordings as ripples represent high resting entropy. Moreover, multiscale entropy (MSE) and functional connectivity (FC) show higher associations in regional fMRI signals at lower temporal frequencies [173].

Emotions instigate suicide, crime, or inspire creative genius. Historically, philosophers, artists, writers, and composers understood emotions better than scientists. Sigmund Freud's attempts to penetrate the hidden structure and personality processes paved the way for scientific analysis of the psyche. He produced a reliable description of the inner life and noted the consequences of emotions for motivational, psychological, and physical problems. Sensory perception creates the belief in self-agency; the belief in free will, which obscure the real origins of motivation.

Although most emotions underlying the innate mechanism of perception, knowledge-acquisition, and decision-making occur below the consciousness threshold, they represent the brain's fundamental motivation [9,34,35], which makes them essential tools of advertisements, for example [124]. Distinct emotions motivate automatically guiding physiological, cognitive, and behavioral responses, which can even contradict conscious intentions. The energy need for emotions and conscious focus involves a broad range of energy utilization based on glucose metabolism and ATP production. Indeed, various mental states, such as mental effort (focus), display corresponding variations in energy use [69,136,135,134,167]. Therefore, part of the energy-requirement of conscious states [19,100,83,119,158], Inzlicht et al., 2018 [184]) might be to drive oscillations beyond the spatial constraints of the connection map.

Physical principles have been increasingly used in the study of cognition [54,75,137,142,150,158]. Recent efforts in consciousness science have studied the thermodynamic consequences of signal processing for single neurons [51,158] and the whole neural system [36,37,147]. In line with the above efforts, the estimated energetic cost of emotions on the brain's energy cycle awaits resolution. In the following, we worked out the mathematical treatment of the thermodynamic consequences of basic emotions posited by the fermionic mind hypothesis (FMH) [34,35]. We will study the energy cost of neural computation by considering the evoked cycle as the Carnot engine. The thermodynamic analysis of emotions can considerably extend our collective understanding of motivation and human behavior.

3. Discussion

3.1. The role of temporal orientation in perception

Current neuroscience recognizes that cognition and thoughts are strongly tied to neural activity. The order associations in learning, speech, thinking, and muscle coordination dictate our psychology's temporal organization [1]. A stimulus representing spatial relationships arrives in the brain, where the sensory organs transform signals into a temporal projection [147]. Neuroimaging studies indicate that cognitive processes within Cartesian coordinates [19,38] differentiate remembered past, perceived present, and imagined future [43,2].

One of the benefits of temporal orientation is distilling experiences into memory and learning. In this regard, cognitive "memory" boosts the ability to control the future. Information compressing reduces processing error (such as Laplace transform) in representing experience and memory retrieval [41,166]. Similarly, in the different phases of deep learning, representation depends on entropic effects that compress data [53,151].

Therefore, a predictive mind must be a holographic system [17], where information compression and orthogonal transformations generate a high fidelity manifold [132]. Because the principle of least action guides objects' movement when moving in space, experience appears to give rise to predictive processing. Intelligent systems optimize their action repertoire between the past and the future [13,37]. *Cognition represents the stationary temporal trajectory* on the synaptic complexity map, representing a potential, the so-called "mental energy" [29,32,40], Schwartz et al., 2005 [185]).

According to emotion theories, emotions have adaptive purposes in human motivation [3,149,148,162,163]. The quality of emotions, such as courage, trust, belief, is an integral part of the neural landscape and represents real, measurable intellectual abilities. Athletes having the same diet, fitness, and coaching regimens produce widely different achievements. The recipe for winning requires a unique personal quality. Emotional intelligence appears to be the primary predictor of runners' finish time [31,114,127]. Emotional intelligence, the ability to identify and manage emotions, is fed by mental energy, which supplies people with the ability to mitigate the consequences of fatigue [94] and negative affect [78]. Rather than personal intention, specific behavior correlates better with peers' decisions [56]!

The often-used term, mental energy, is a consistent and long-term ability [32,40], Schwartz et al., 2005), arising from real, formidable abilities, such as persistence and determination. Decision-making, empathy (Cameron et al., 2017 [186]), focus, and vigilance [19,100], Zohar et al., 2003 [187]) represent substantial energy needs, making their availability a personal privilege. For example, fatigue and negative states can compromise performance (Loy et al., 2018 [190]; [106], whereas motivation, such as the expectation of reward or goal-enhancing events, mitigates fatigue and can push performance beyond past limitations [100], Zohar et al., 2003). Depression is an inability to act or even pay constructive attention [73]. For example, individuals with depression may want to stop themselves from ruminating but are often unable to do so because the negative thought pattern is primarily automatic [157].

It has recently been shown that near orthogonality of large dimensional random vectors can produce holographic projection [97]. Sensory perception translates spatial relationships into temporal rhythms, an orthogonal organization, by the hippocampus's place cells [169]. The holographic projection integrates temporally distant identities in perception and decision-making to form and orient the self [34,35,37]. Scale-free activations provide a ''temporal integration'' with the faster frequencies nested within the more powerful slower ones. Therefore, temporal manifestations of consciousness arise from the synchrony of psychological and neuronal qualities. The temporal activities of the resting state correlate with self-consciousness [179]. The evoked states organize around the resting state's fundamental constancy (reviewed by [155], allowing the thermodynamic consideration of the evoked activities.

4. Thermodynamic considerations of brain activities

Physical processes can be dissipative, reconstructing the past, and intelligent, those that anticipate the future [28]. The first kind, exothermic processes dumps entropy, and energy into its environment, whereas the latter endothermic actions absorb entropy while requiring energy to operate. The thermodynamic computation of the cortical neuron provides an example of the second possibility. Fry analyzed the thermodynamics of action potentials generated by one neuron [51]. The quasi-hierarchical nature of the brain allows us to generalize his conclusions for the energy-information exchange of stimulus. Extending the thermodynamic considerations onto the whole brain delineates the crucial role of energy in cognition [36,37,147].

The Carnot engine is a theoretical thermodynamic cycle first proposed by the French engineer Sadi Carnot [144]. It defines the maximum possible efficiency of a heat engine during converting heat into work when working between two reservoirs. It has been shown that cognitive or computational effort, such as thinking, focus, and even meditation, is taxing [77,101]. Conscious control drains mental resources in proportion to task difficulty [176,170,103], indicating their connection to energy consumption and thermodynamics (Cameron et al., 2017; Zohar et al., 2003; [19,100,147].

The maximum amount of work a thermodynamic process on a constant volume can perform is equal to the negative of the change in the free energy [171]. In the brain, this leads to the cognitive cost of mental effort. Demanding cognitive tasks, such as mental arithmetic, lead to a subjective feeling of mental exertion [68]. Strenuous tasks lead to cognitive fatigue, characterized by a subjective dimension – i.e., feeling of exhaustion, a decreased willingness to engage in mental activities [19,100,64], Loy et al., 2018; [106], Zohar et al., 2003).

The brain's regulation of its complex electrical activities satisfies the laws of thermodynamic [25]. The brain's frequency-dependent energy consumption maintains its self-organizing activities and fuels the modification of synaptic maps and corresponding mental change [29]. Excitation produces an intricate play of sharply changing, the so-called evoked potential [160]. As a computing object [51,36,158,93], evoked activities reflect an enhanced ''temperature.'' Early consideration of brain temperature measured disequilibrium and heterogeneity at various spatial and temporal scales [117]. However, emotional temperature relates to the degree of information transmission ability. The ability to transmit information increases with the frequencies (higher frequencies transmit more information than lower oscillations per unit time).

The sensory system is a spontaneous information transmitter, governed by a stimulus. Potentials and electric flows between the cortex and the limbic brain formulate automatic and involuntary energy-information exchange with the environment. The resulting brain frequencies depend on the environmental entropy. It is generally accepted that order, beauty triggers calm, happy states with lower frequencies than the stressful states originating in environmental disorder. Therefore, the brain ''pays'' from the sensory information by the elevated brain oscillations. Sensory perception can be considered a thermodynamic cycle [36,51].

The recurring resting-state ensures the *particle-like stability* of the mind, according to FMH [34,35]. Electromagnetic gradients form highly fluid, wave-like activation patterns on the cortical surface, positively correlated among spatially distributed cortical areas (reviewed by [110]). The brain's harmonic modes, defined as connectome harmonics, display self-organization of frequency-specific building blocks [43,5]. We shall investigate how thermodynamic principles ascribe correlated brain activity, i.e., the thermodynamic cost of neural computation. Recent studies have shown examples of the proposed loops, such as specialized learning. Here, the increasing synaptic strength forms an attractive loop, reducing the degrees of freedom. However, the second phase of learning enhances the degrees of freedom by integrating the learned information via the reversed Carnot cycle. The synaptic flexibility corresponds to self-confidence due to greater oversight of concepts and understanding [181].

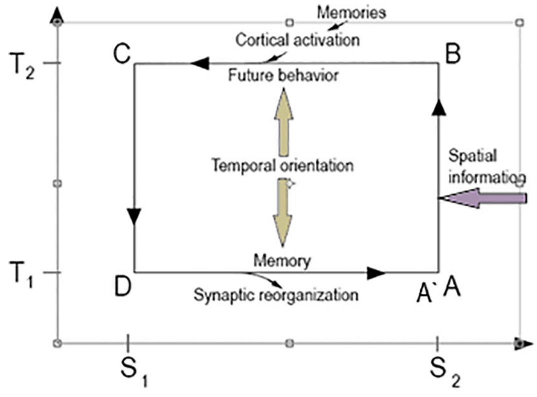
4.1. Negative emotional states

Despite their varied typical cultural and brain activity profiles [74,90,105,112,164,182], and novel relationship between task and resting-state brain activity [57], emotions represent only positive or negative energy conditions [62,71]. The activity patterns elicited by different tasks from the Human Connectome Project can also be reconstructed from a minimal subset of functional harmonics, indicating the interrelated relationship between task and resting-state brain activities.

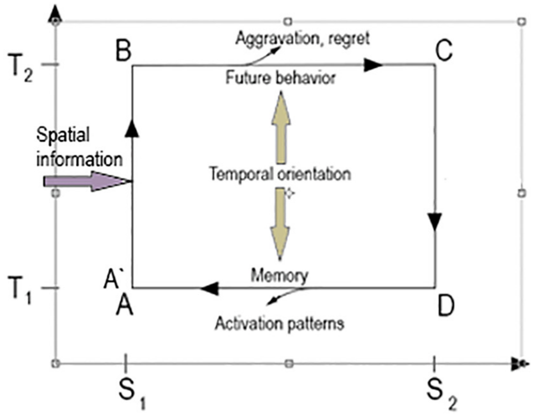
Network harmonics are sufficient to track large-scale cortical activity during stimuli processing [58]. Conscious states are related to different connectome-harmonic repertoires [6,92]. Recent studies corroborated the connection of slower oscillations with positive emotions and enhanced brain frequencies with negative mental states [12,143]. The central tenet here is that by considering the brain's energy state (mental energy) as an analog to potential energy in physics, the Carnot cycle can model the brain's operation (Fig. 1).

Negative emotional states have more significant energy requirements than positive emotional or neutral mental states [69,71,136,135,134]. In negative states, the detailed oscillations dissipate energy, narrow focus (deterministic), and reduce temporal dimensionality [165] and forming a temporal pressure. Enhanced brain frequencies may trigger long-term potentiation [14], which increases the likelihood of activating the same synaptic path [61]. Repetitive activations give rise to regret, remorse, and aggravation [27]. Stress and anxiety reduce the degrees of freedom (Rowe and Fitness, 2018 [188]), blinding people for the possibilities open to them (Lupien et al., 2007 [189]). In anxious individuals [108], decreased theta band synchrony typically produces task-irrelevant signals and inferior post-error behavior [68].

Therefore, managing emotions is like managing a car's engine; operating the air-conditioning, for example, causes the fuel economy to deteriorate. Likewise, attention determines the outcome of mental effort [87]. For example, children's views about abilities and intelligence can set them on different trajectories of motivation and learning (see [18] for review) toward self-regulation and motivation [60] or failure. Therefore, attention and focus is the most precious resource to waste.



Reverse Carnot cycle
Mental energy gain



Carnot cycle
Mental energy loss

Fig. 1. The consequences of intelligent computation. The neural system uses substantial resources to recover the resting state during the evoked cycle. However, neural computation changes the synaptic complexity, which has consequences to the organism's ability to respond to future challenges. The reversed Carnot cycle accumulates energy and entropy (the entropy at the end of the cycle is A′ where S (A′) > S (A)). In contrast, the entropy at the end of the Carnot cycle is A, ′ where S (A′) < S (A).

After having received a signal containing ΔI bits of information, a system of the brain can perform at most

$$W = -k_B T \, \Delta T$$

units of work on its surroundings using that information. W the system's performance of work k_B is Boltzmann's constant, and T is the temperature of the system in Kelvin.

The reduction of entropy in negative emotions is an exothermic condition, which damages emotional regulation and intellect through deterministic oscillations. Exothermic brain states radiate out energy via aggravation, critical tendency, or physical violence. Another facet of mental damage concerning information entropy is that it might occur due to the unsustainable accumulation of information. In other words, the extended effort to process information overwhelms the neural system and deteriorates into immune and mental problems [72,79].

Negative affect was associated with increased medial PFC positive reappraisal activation and decreased positive reappraisal activation in the left insula and cognitive flexibility regions (putamen and cerebellum) [67]. The increase of the entropy of the environment, on the one hand, parallels with a loss of synaptic complexity and resting entropy, on the other hand (Rowe and Fitness, 2018). Thus, mental energy degradation might be the first symptom of mental, hormonal, and immune problems. Although the adverse effects are hard to notice, mental degradation accumulates over time.

For example, failure of emotional management can lead to the explosive 'boomerang' effect through violence towards others and the self—following emotional suppression [85,129]. Suppression cannot easily be separated from subsequent discharge. Emotional suppression also lower authenticity, emotional well-being, relationship quality, and responsiveness to loved ones [86]. Sigmund Freud has pointed out the role of sexual inhibition in disabling maladjustments and emotional inhibition in developing chronic conditions, such as cancer [70]. Emotion suppression has been associated with a range of adverse health outcomes, causing especially damaging outcomes in the long-term [85,129].

Shame is another difficult emotion to deal with, leading to two general strategies: attacking the self or attacking others [172]. Directing the accumulated energy inward triggers a cascade of events, such as the production of stress hormones [7] and immune suppression (reviewed by [109,105]).

Anxiety and depression represent mental energy-poor states [140,177]. Studies in psychology have found that insecure and guilty people perceive themselves as heavier and their chores more burdensome [30]. In recent rodent's experiments, repeated stress exposure, which reduced plasticity by corrupting connectivity within the medial PFC, drove depressive behavior [89,180]. It should also be noted that depression is associated with the stagnation of vital processes and an incapacitating slackening of the flow of time [157]. Depressive symptoms and depression-related negative cognitions were negatively correlated with emotional flexibility [11] and reduced synaptic complexity [175]. The severity of cognitive impairment was positively related to brain entropy reduction [174].

Both the slower oscillations (positive emotions) and enhanced brain frequencies (negative mental states) expand time perception [113,126]. Their contrasting physiologies arise from the fact that low frequencies form negative, whereas high frequencies form positive temporal curvatures [165].

Recent studies have confirmed the topological nature of sensory representation. Cognitive states warp spatial representations throughout the brain [76]. The slowing of time perception in both positive and negative emotional states and their contrasting physiological consequences has not been addressed in neuroscience. For this purpose, highly sensitive temporal methods, such as corticoelectrogram, would be useful. The dimensionality transformations of time caused by brain frequencies permit the possibility that mental energy changes might represent differences in mental volume.

A closed system can exchange energy (as heat or work) in thermodynamics, but not matter, with its surroundings. Biological organisms are open systems. They exchange energy with their surroundings, and they consume energy-storing molecules, do work, and release metabolites. The above description does not apply to the brain. Although the blood supplies the brain with oxygen and energy source, sensory perception forms a closed cycle [65,91,115]. Energy-information exchange with the environment exclusively occurs via the sensory organs. The sensory system is a vehicle for information exchange.

Steady-state thermodynamic engine processes formulate a closed loop with a vanishing integral. Thus, integration of the differential energy balance dE = δQ − δW over the full cycle yields

$$W = \oint \boldsymbol{\delta W} = \oint \boldsymbol{\delta Q} = Q_{in} - Q_{out}$$

where W and Q are the total work, and net heat exchanged for the cycle. Moreover, $Qin > 0$ is the total heat transferred into the cycle, and $Qout < 0$ is the total heat transferred out. The network and net heat are positive for a clockwise process—a heat engine— and are negative for a counter-clockwise process—a heat pump.

In the following, we examined the thermodynamic consequences of negative emotions. The amount of thermal energy transferred in the Carnot cycle is the following:

$$Q = \oint_{A}^{B} TdS$$

The area inside the cycle will then be the amount of work done by the system over the cycle.

$\mathrm{W} = \oint \mathrm{PdV} = \oint (\mathrm{dQ} - \mathrm{dU}) = \oint (\mathrm{TdS} - \mathrm{dU}) = \oint \mathrm{TdS} - \oint \mathrm{dU} = \oint \mathrm{TdS}$

Since dU is an exact differential, its integral over any closed loop is zero: it follows that the area inside the loop on a T-S diagram is equal to the total work performed

The amount of energy transferred as work is

$$\mathrm{W} = \oint PdV = \oint TdS = (T_H - T_c)(S_B - S_C)$$

The total amount of thermal energy transferred from the hot reservoir to the system will be

$$Q_H = T_H(S_B - S_A)$$

The efficiency η is defined to be:

$$\eta = \frac{W}{Q_H} = 1 - \frac{T_C}{T_H}$$

For the reversed Carnot cycle, the efficiency is defined to be:

$$\eta_{reversed} = \frac{T_H}{\mathrm{TH} - \mathrm{TL}} = 1/\left(1 - \frac{T_C}{T_H}\right)$$

where

W is the work done by the system (energy exiting the system as work),

$T_C$is the heat taken from the system (heat energy leaving the system),

$Q_H$is the heat put into the system (heat energy entering the system),

$T_C$is the absolute temperature of the cold reservoir, and

$T_H$is the absolute temperature of the hot reservoir.

$S_B$is the maximum system entropy

$S_A$is the minimum system entropy

P is the pressure, V is volume

dU is the change in internal energy U of the system

Intellect is known to be related to the production of an expansive range of emotions—the smaller the temperature difference, the smaller the efficiency. Because emotions represent the brain's operating temperature, they represent the mind's intellectual limitations. The greying of emotions during aging (smaller temperature difference) might explain the learning difficulty of older people. The greying of emotions also appears to be one of the first symptoms of many mental diseases [4,104], such as dementia (FTD) and AD [22] and Alzheimer's [4,15,175]. Mental decline (loss of mental energy) correlates with mental and emotional limitations.

The loss of signal complexity is also proportional to the degree of cognitive decline [55,89]. Mental and emotional rigidity in presymptomatic patients might result from hyperconnectivity. Enhanced structural connectomics (loss of complexity) may relate to problems of emotional regulation [45,152] and corruption of cognitive functioning [15,133]. Therefore, entropy parallels degrees of freedom in the resting brain. The presymptomatic structural changes listed above are possible precursors of emotional problems.

Next, we will examine the synergy between the brain state and the environment.

A topological view of this synergy between the brain and the environmental energy cycles exhibits strong proximity both spatially and descriptively. The spatial strong proximity [120] of the brain and environment is in the form of temporally overlapping cerebral energy and environmental energy readings (*e.g.*, the occurrence energy highs and lows of the one set of readings overlaps with the occurrence similar readings of highs and lows in the other during the same timeframe). For example, let A and B represent nonempty sets of recordings of brain and environmental energy recordings that are temporally concomitant *in situ*. The spatial form of strong proximity is denoted by From the strong proximity axiom ([121], p. 16), we have

$$A \overset{w}{\delta} B \text{ implies } A \cap \mathrm{B} = \varnothing,$$

i.e., the two sets of energy readings overlap. There is a also a descriptively strong proximity between the two sets of energy readings. The descriptive form of strong proximity is denoted by $\underset{\vartheta}{\overset{w}{\delta}}$ The subscript ϑ refers to a mapping ϑ: A → $\mathfrak{R}^n$ on the set of readings A into an n-dimensional feature space $\mathfrak{R}^n$ defined by $\vartheta(x)$ (a feature vector in $\mathfrak{R}^n$) that is a feature value of a reading $x \in A$. Similarly, there is a mapping ϑ: A → $\mathfrak{R}^n$ on the readings in B into the feature space $\mathfrak{R}^n$ The two sets of energy readings with common descriptions give rise to a descriptive intersection (denoted by $\cap_\vartheta$) of the two sets:

$$A \cap_\vartheta B = \{(x \in A \cup B : \vartheta)(x) \in \vartheta(A) \& (x) \in \vartheta(B)\},$$

i. i.e., there is at least one cortical energy reading (e.g., cortical energy amplitude) in A that has the same description as an environmental energy reading (e.g., environmental energy amplitude) in B. From these structures, we can elicit a strong descriptive proximity between A and B ([121], p. 28-29) in terms of

$$A \cap B = \varnothing \text{ implies } \mathrm{A} \underset{\vartheta}{\cap} \mathrm{B} \neq \varnothing.$$

i.e., overlapping energy readings implies an overlap between the descriptions of the two sets of readings. This observation leads to the following descriptive proximity property:

$$A \underset{\vartheta}{\overset{w}{\delta}} B = \varnothing \text{ implies } A \underset{\vartheta}{\cap} B \neq \varnothing.$$

The importance of this pair of proximities lies in the fact it is then possible to derive Leader uniform topologies on pairs of sets of energy readings. This is done in the following manner. Start with a collection of sets of cerebral energy readings $\cup 2^{\mathrm{A_i}}$ and a collection of environmental energy readings $\cup 2^{\mathrm{B_i}}$ gathered within the same timeframe. For each given subset $\in \cup 2^{\mathrm{A_i}}$, find all $\mathrm{B} \in \cup 2^{\mathrm{B_i}}$ such that $A \underset{\vartheta}{\overset{w}{\delta}} B$. Doing this for each given set of cerebral energy readings leads to a collection of clusters of strongly near sets of readings. In effect, we have topologized the collections of energy readings by introducing a Leader uniform topology [88,122] on the space of energy readings. An essential outcome of topologized energy readings is the introduction of a search space in which clusters of readings exhibit spatial and descriptive proximities.

4.2. Consequences for intellect (positive emotions)

The system's history and current state are just as crucial in determining the quality of neuronal activation as the stimulus itself [123]. Thus, the observer's (i.e., the brain) state determines the stimulus's information value. The observer's role in information processing means that information processing is holographic; the degree of comprehension or understanding (manifested as increasing synaptic complexity) has a high subjective quality, the observer effect. High performers in intelligence tasks showed lower brain activations, arising from slower oscillations [12,143] and indicating higher neural efficiency (Haier et al., 1988 [191]; Poldrack, 2015 [192]; [168]. Cognitive flexibility also predicted intellectual humility and openness to new evidence [183].

Research has shown that positive emotions play a pivotal role in coping, adjusting to life changes, making friends, engage in proactive social relationships with others [39,118], self-reliance, and flexibility thinking [96]. For example, students' study-related positive emotions were related to better academic performance through positive relationships with their levels of psychological capital (i.e., efficacy, hope, optimism, and resilience) [20]. Improving self-regulation and motivation is possible even in early childhood [60].

Because the temporal dimensionality [165] is inversely proportional to stress, the temporal expansion permits patience via self-control. A mental slowing down affords "time" for a balanced response. Therefore, self-control is part of emotional intelligence, and it is often associated with mental energy and even intellect [44]. It has been proposed that these endothermic processes may control the future by enhancing Intellect [51,178], see Fig. 2.

The enthusiasm and energy that characterize awe and other positive emotions reflect an information-free state. Because low frequencies lack details (Fig. 3, top) and engage broader cortical areas, they inspire associative representations [82,95]. The slower oscillations can access a high number of microstates to produce almost any thought. Positive emotions, such as joy, interest, contentment, and love, broaden the thought-action repertoire, increasing the degrees of freedom [46]. In line with the aforementioned slow oscillations, the temporal variability of the resting-state connectivity, i.e., high entropy correlates with fluid intelligence [181].

In psychology, mental energy fuels intellectual qualities. The transformation of incoming sensory information into neural complexity might be the source of increasing personal intellect. The reversed Carnot cycle increases the mental energy and, consequently, the neural system's resting entropy (Figs. 2 and 3). The synaptic map represents an energy potential for future action. Mathematically, Landauer's principle might explain how the information value of stimulus transforms into synaptic complexity, i.e., mental energy [84].

$$E = k_B\, T\, ln \qquad (2)$$

Entropy in a physical system is the number of existing microstates, but in the brain, it is the number of possible neural configurations of synchronized or connected brain networks. Access to a significant number of neural states predicts complex behavioral performance (mental energy). Therefore, in contrast to the disorder of the physical world's information-rich condition, resting entropy represents the brain's energy potential. The difference might arise from the temporal, holographic nature of neural computation.

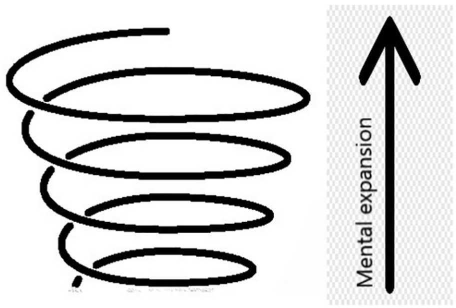


Fig. 2. The evolution of mental energy. The loops of energy turnover centered on the resting state provides the basis of mental changes and intellectual development.

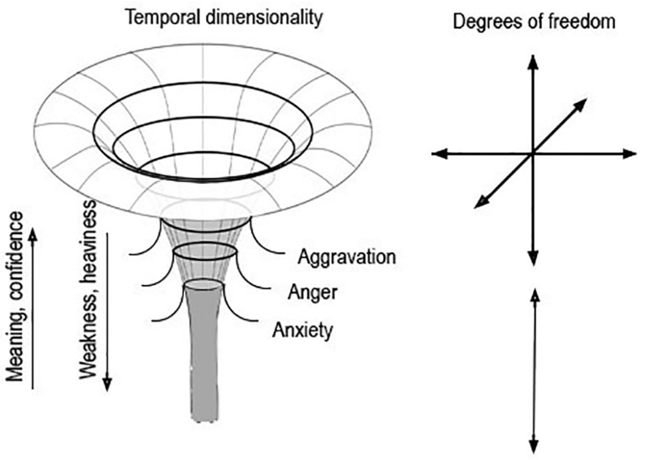


Fig. 3. The effects of emotions on mental freedom. Positive emotions and meaning expand the freedom (top). Aggravation and anxiety waste time and energy, causing mental rigidity (bottom).

The efficiency of the Carnot cycle determines the outcome of interaction (and the resulting emotions). It is important to note that the working fluid absorbs heat from the boiler in the Carnot engine and releases heat to the cooling water in the "condenser." The limited work produced by one cycle turns work production into a gradual stepwise process. The same requirement applies to the brain. The limited synaptic organization achieved in one cycle means that the mental changes accumulate over time. Learning, mental transformation takes repeated practice over time.

Our calculations support findings in psychology and social sciences that psychological change and mental evolution occurs in close synchrony with the environment. Beginning with the famous studies by Selye [141], many have shown the role of the environment in behavior. Spontaneous brain activities (intrinsic), and those triggered by a stimulus (extrinsic), represent the neural underpinning of reasoning [50]. The environment's role in triggering mental changes *limits free will for determining the Carnot cycle's direction*, which entails the attitude.

The thermodynamic considerations of emotions can explain the compounded nature of attitude in long-term well-being. In agreement with famous studies in psychology, attitude, and acceptance have an immense role in coping with personal and professional challenges [21]. The above mental characteristics lend emotional stability, resilience, and persistence.

Our argument might explain the long-term contrasting consequences of mental changes [107] due to positive and negative psychologies (Fig. 3). Therefore, learning and spiritual practices can overturn the adverse circumstances; inversely, cynicism can neutralize outside support. Our investigations explain that mental energy, being an essential consideration in psychology, is the brain's structural quality [29,32,40], Schwartz et al., 2005).

4.3. Social consequences

Our analysis attempts to connect basic research in neuroscience with psychobiology, clinical diagnostic and therapeutic insights. We show how the temporal orientation of cognition creates a balance between the mind's (top-down) processing of information (mental energy) and cognition as sensible (bottom-up) reception of information (sensory processing).

The above argument shows the importance of analyzing emotions based on valence and arousal [62]. Emotional valence describes the extent to which an emotion is positive or negative, whereas arousal refers to its intensity, i.e., the associated emotional state [23] and reviewed by [128]. We have also shown how mental energy evolution leads to Bayesian belief updating and the Markov decision process [48,47,50,49].

The social environment is an excellent determinant of the mindset of behavior in animals and people. Positive psychology recognizes the close relationship between social climate and resource availability. In the late nineteenth century, Peter Kropotkin found that species from bacteria and fish to mammals and birds appear to lean toward generosity and cooperation when faced with abundance. From ants and bees to falcons, swallows, gazelles, and buffalos, as well as herds of wild horses, tribes of dogs, wolf packs, and communities of people form cooperation and generosity when faced with biological richness and supply abundance [159,26,81]. Our results suggest that positive environments occur encourage the generosity and cooperation by supporting mental energy growth. Desirable population structures promote cooperation [161].

When the reduction of supplies reaches a tipping point, generosity disappears [159]. After the tipping point, defections sweep through the population (Hoek et al., 2016) [193], the lack of resources inflicts a cognitive burden, which negatively affects IQ [59], Makharia et al., 2016; [98]. The poor's lack of generosity originates in mental exhaustion rather than personality defects. The above considerations also might explain poverty's role in negative personality transformations. Conspiracy theories, terrorism, and crime reflect the wide-spread distrust in governments, public institutions, and even science. We propose that the loss of degree of freedom shown in our earlier discussion occurs through distrust. Therefore, interventions to provide basic social safety are effective to raise the human race's overall cognitive performance.

5. Conclusions and future directions

We connected the thermodynamics of the brain's evoked cycle to the psychology of motivation. The connection of slower oscillations with positive emotions and enhanced brain frequencies with negative mental states inspired our consideration of the brain's energy state (mental energy) as an analog to potential energy in physics. Our analysis supplies a mathematical connection between neuroscience and psychology by uncovering emotions, the forces of motivation, as reflections of the brain's energy balance. Recognizing emotions as the energy states of the brain can provide more effective tools in psychology.

We have shown that basic physical and information-theoretic principles can describe intelligent computation; the endothermic slowing of time perception might reflect information transformation into intellect. The reversed Carnot cycle enhances synaptic flexibility, the ability to produce new thoughts and ideas. Therefore, supportive environments and basic personal safety inspire generosity, confidence, trust, and cooperation. Positive emotions are conducive to success, by increasing future degrees of freedom.

The Carnot cycle equivalence indicates that lower resting entropy leads to mental degradation via an exothermic process. Although intermittent short time stress can be beneficial (preserve mental energy accumulation), repeated or extended exposure to stress, such as systemic adversity, such as poverty, cause of adverse personality transformations. Aggravation, rumination, and critical tendencies dump energy onto the environment and induce distrust through mental dysfunction. Attractive loops become the source of repetitive thought patterns, the loss of the degrees of freedom.

Supporting mental growth can be instrumental in reversing the predicted global acceleration of mental diseases. The above understanding is an essential piece for policy guidance for governments in navigating the post-pandemic milieu. Verifying the thermodynamic underpinning of mental changes could revolutionize psychological and social sciences and support social and educational reforms.

The ability to transform information into energy, i.e., intellect, seems to be the brain's essential quality (as shown by Landauer's principle). Gradual synaptic changes accumulate mental energy, but the mind updates its beliefs in a discrete fashion. The energy gain of the neuronal system is intellectual evolution, which is closely intertwined with the environment's entropy. (The Carnot engine's working fluid absorbs heat from the boiler and releases heat to the environment.)

The immense role of the environment in mental changes also proves that free will is limited to choosing the Carnot cycle's direction. Our calculations might contribute to the impetus for turning psychology into hard science. The above considerations might inspire answers to philosophical and scientific questions such as the hard problem of consciousness, the relationship between brain and mind, and even free will. The principle indicates that one-day intellectual computation via AI can become significant in enhancing intellectual possibilities and cosmic order.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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