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REVIEW PAPER

The thermodynamic brain and the evolution of intellect: the role of mental energy

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Abstract
The living state is low entropy, highly complex organization, yet it is part of the energy cycle of the environment. Due to the recurring presence of the resting state, stimulus and its response form a thermodynamic cycle of perception that can be modeled by the Carnot engine. The endothermic reversed Carnot engine relies on energy from the environment to increase entropy (i.e., the synaptic complexity of the resting state). High entropy relies on mental energy, which represents intrinsic motivation and focuses on the future. It increases freedom of action. The Carnot engine can model exothermic, negative emotional states, which direct the focus on the past. The organism dumps entropy and energy to its environment, in the form of aggravation, anxiety, criticism, and physical violence. The loss of mental energy curtails freedom of action, forming apathy, depression, mental diseases, and immune problems. Our improving intuition about the brain's intelligent computations will allow the development of new treatments for mental disease and novel find applications in robotics and artificial intelligence.

Keywords Mental energy · Carnot engine · Consciousness · Depression · Emotions · Mental disease

Mental energy or intrinsic motivation Cognitive and physical effort is associated with different cost functions (Kool and Botvinick 2018). 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 (Ryan et al. 2016). It is a long-term ability based on mental fluidity that allows trust, belief, and confidence. Intrinsic motivation allows a consistent exertion of mental effort toward achievement by increasing future freedom of action.

Mental effort Mental effort is how hard a person tries to perform on some task. Prolonged periods of demanding cognitive activity or disease lead to fatigue that negatively affect performance. Mental fatigue has a more significant detrimental effect on physical performance than physical exhaustion (Coutinho et al. 2018), which can be remedied by rest or the recovery of health.

Mental fatigue Mental fatigue is a psychobiological state caused by prolonged exertion that can damage cognitive and exercise performance (Meeusen et al. 2020).

> …economists instinctively assume thinking as a costly activity…Mental effort is like physical effort-people dislike both, and will do more of both if you pay them more.—Camerer and Hogarth (1999)

Introduction

The connection between the mind and the brain has remained an intriguing puzzle throughout human history. Idealism, represented by Kant, Hegel, and many Eastern beliefs, asserts the primacy of consciousness. Materialism is the dominant metaphysical framework in science. Neuropsychology has a general expectation that brain mechanisms are sufficient to explain all psychologically described phenomena (Schwartz et al. 2005). Dennett, Churchland, and other materialists, who consider the mind just an illusion produced by brain circuits, favor the idea. The two contrasting views have found a compromise in dualism. Descartes, echoed by Popper, Eccles, Chalmers,

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and others in western thought, posited the separation of physical bodies and the world of mental states. The following argument contributes to recent findings in neuroscience and psychology to the discussion.

The hierarchical organization of information processing gives rise to the time dependence and subjectivity of motivation. If motivation were a vector, its length would represent the amplitude or intensity of pursuit, and the angle of the vector would represent its focus on a specific goal (Simpson and Balsam 2015). An uncanny ability to automatically (independent of consciousness) reorient itself against disturbances imposed on it by the environment forms the basis of the mind's homeostatic regulation. Applying homeostatic principles to simulated networks improves their correspondence significantly to empirical fMRI data (Rocha et al. 2018). Self-determination theory (SDT) considers competence, which is protected by a restorative response, a basic psychological need for well-being (Fang et al. 2018). Active Inference Theory applies the free energy principle to action (Friston 2012, 2018; Allen and Friston 2016). Any adaptive change in the brain will minimize free-energy (prediction error, cost). The following discussion incorporates the above theories by showing how psychology and emotions arise from the self-regulation of the cortical brain (Deli 2015).

The stability of the inner world of consciousness (Smitha et al. 2017) forms the resting-state networks (RSNs). In the absence of stimuli, mind-wandering, autobiographical memory, future thinking, and introspection (Grieder et al. 2018) integrate motor and sensory information into an abstract model of the world (Musall et al. 2019). The constancy of the self depends on the stability provided by the resting state, which is maintained independently of conscious awareness. Its extensive geodesic distance from primary sensory and motor regions permits abstract representational hierarchies of dense information integration, connectivity, and routing hubs (van den Heuvel et al. 2012; Margulies et al. 2016). The integration of the organism's past and present orchestrate future behavior based on the brain's internal model (Fingelkurts and Fingelkurts 2014).

High signal complexity (entropy) of the default mode network (DMN) appears to be crucial for cognitive function and the maintenance of mental health (Grieder et al. 2018). Resting neuroimaging signals show that fluid access to variable neural states predicts complex behavioral performance and intellectual capacity. An almost equal likelihood occurrence of ripples of activations (representing microstates) represents high resting entropy (Fingelkurts and Fingelkurts 2014). Although resting thoughts are fleeting, the high degrees of freedom grants the ability to produce almost any thought.

Boltzmann explained entropy as the number of microstates of the system. On the other hand, information entropy (Shannon's entropy) is the average rate at which a stochastic source of data produces information. Measuring and evaluating the entropy of the neuronal system might open a new way for diagnosis and therapy in psychology and psychiatry, and cognitive sciences (Belavkin and Ritter 2003; Gabora 2016; Hirsh et al. 2012; Sayood 2018; Smith et al. 2018).

Traditional approaches to entropy estimate the degree of regularity of a time series on a single time scale (Li et al. 2018). Complexity, such as the dynamics of activities, can be defined as the amount of nonlinear information that a time series conveys over time (Omidvarnia et al. 2018). The simultaneous coexistence of subcritical and supercritical dynamics in different neural regions stretches the parameter range forming self-organized criticality (Hesse and Gross 2014). Entropy in several crucial brain areas correlates with intelligence in both verbal and performance measures (Saxe et al. 2018). The relation was most strongly observed in the prefrontal cortex, inferior temporal lobes, and cerebellum. The multiscale entropy (MSE) approach makes use of a method termed "coarse-graining," which provides an entropy profile across multiple time scales and differentiates meaningful complexity from uncorrelated randomness (Li et al. 2018). The multiscale entropy (MSE) and functional connectivity (FC) show high associations at lower temporal frequencies (Wang et al. 2018).

Due to the increasing entropy in the environment, a constant flow of information bombards our sensory system (Schrödinger 1945). The cognitive or computational resource of the neural tissue is limited at any one time (Inzlicht et al. 2018), while neuronal signalling and metabolism are tightly coupled at the local level. The stabilized internal representations stay closer to their attractor fixed-points. Perceptual binding and feedback/feedforward waves improve the perception of external inputs by reducing neural noise (Buzsaki et al. 2013). The energy need of mental effort (focus) inspires utilizing physical principles for the analysis of cognitive processes (Deli et al. 2018; Fry 2017; Street 2016). Recent efforts in consciousness science have studied the thermodynamic consequences of signal processing. Although the energetic cost of emotions in signal processing has been established, their specific role in the brain's energy cycle awaits resolution. We examined the thermodynamic consequences of basic emotions posited by the fermionic mind hypothesis (FMH) (Deli 2020).

Discussion of mental energy

The energy need of muscle action is straightforward, but the mental effort is independent of physiological variables traditionally associated with endurance performance (heart rate, blood lactate, oxygen uptake, cardiac output, and maximal aerobic capacity). Nevertheless, cognitive or computational effort, such as thinking, focus, and even meditation, is taxing (Kool and Botvinick 2018; Martin et al. 2018), and conscious control drains mental resources in proportion to task difficulty (Warm et al. 2008; Van Cutsem et al. 2017; McMorris et al. 2018). However, mental energy permits one to engage in and enjoy effortful cognitive activities for their own sake (Inzlicht et al. 2018). Mental energy (or g factor) is autonomous self-regulation (Ryan and Deci 2008) toward the pursuit of internal goals.

Affective neuroscience has revealed the functional integration of emotions and cognition. Emotions are part of the brain's energy architecture (Barbey et al. 2014; Touroutoglou et al. 2015). As such, conflict elicits many of the hallmark features of emotion, including valence judgments, physiological arousal, and subjective emotional experiences (Inzlicht et al. 2018; Saunders et al. 2017). Cognitive control can be understood as an emotional process (Inzlicht et al. 2015); therefore, emotional intelligence (the ability to identify and manage emotions) is closely related to mental energy. For example, in long-distance runners, emotional intelligence was found to influence performance to a more considerable extent than rigorous training (Rubaltelli et al. 2018).

The energy need of attention means that decision-making, empathy (Cameron et al. 2017), focus and vigilance (Zohar et al. 2003; Buzsaki et al. 2013; Manohar et al. 2018) depletes vitality, resulting in fatigue and negative emotions (Inzlicht et al. 2015). Several neurotransmitter systems (dopamine and adenosine) in the prefrontal cortex and the anterior cingulate cortex can compromise endurance performance (Loy et al. 2018; Meeusen et al. 2020),

Lack of mental energy means real, formidable challenges to achievement and should not be confused with fatigue. While fatigue can compromise performance temporarily, mental energy is a consistent ability (Schwartz et al. 2005). Although small lifestyle changes may improve feelings of fatigue, enhancing mental energy requires long-term development (Boolani et al. 2019) and comprehensive interventions. Intellect is flexible (Heintzelman et al. 2013). In studies, mental energy could be improved by elevated dopamine and norepinephrine transmission and binding (Loy et al. 2018), whereas fatigue was related to serotonin and inflammatory cytokines and reduced histamine binding.

What is the neurological background of differences in performance? The prolonged performance of a demanding cognitive task increases cerebral adenosine accumulation, which may lead to a higher perception of effort experienced during subsequent endurance performance (Pageaux et al. 2014). Highly anxious individuals must exert considerable cognitive effort to perform at the same level as less anxious people (Inzlicht et al. 2015; Saunders et al. 2017). Distress encompasses negative moods, and a lack of confidence and worry reflects negative self-referent cognitions. Insecurity causes avoidance of mental exertion whenever possible (Inzlicht et al. 2015). There is ample evidence that immune signalling is intimately tied to the neural processes governing social behaviors (Kopec et al. 2019). Because immune challenges impair social behavior by altering neuro-immune signaling in brain regions important for reward/motivation, the dopaminergic reward circuitry is engaged during social behaviors and impacts immune function. Motivation, such as the expectation of reward or goal-enhancing events, mitigates fatigue, and can push beyond the usual performance limitations (Manohar et al. 2018; Zohar et al. 2003).

The role of interaction in mental change

The brain's rich club organization ensures minimal energy conformation during state transitions (van den Heuvel et al. 2012; van den Heuvel and Sporns 2011). Active inference minimizes an organism's exposure to uncertainty or surprise (Pepperell 2018a, b). We propose that such minimal energy conformation is analog to the principle of least action in physics. The stationary action has a temporal equivalent in the predictive intelligent processing that calculates its response based on experience. As material systems observe the principle of least action when moving in space, intelligent systems optimize their action repertoire between the past and the future (Friston et al. 2017).

Energy metabolism is necessary for proper cell function and viability, but it is also crucial in higher brain functions such as memory processing and behavior. Investigating the brain's energy relationships can uncover the physical underpinning of consciousness (Pepperell 2018a, b). The brain maintains homeostasis because incompatibility with expectations triggers emotional reactions (Selye 1974). Repeated activation of the same neuronal connections requires less energy, resulting in less and less emotional involvement, forming automatic activation patterns.

Sensory interaction, the basis of mental homeostasis

The neural tissue generates spontaneous oscillations. In unconscious states, such as anesthesia, electric activities are limited to the anatomical repertoire (Uhrig et al. 2018). The energy-requirement of consciousness states (Buzsaki et al. 2013; Manohar et al. 2018; Kyong et al. 2015; Pepperell 2018a, b; Street 2016; Inzlicht et al. 2018) drive oscillations beyond the connection map. Specific neural activation patterns (i.e., dorsal anterior cingulate cortex) as well as accompanying autonomic indices (i.e., skin conductance response) hold predictive information on individual performance (Köhler et al. 2018). Because the cost of cognition is also often evaluated as the amount of information needed to update earlier beliefs, the effort of tasks is highly variable and subjective (Koechlin 2007).

Evoked potential in the human brain is a complex play of sharply changing potentials (such as N100 and P300), see Fig. 1 for a greatly simplified representation (Sur and Sinha 2009). Electromagnetic gradients form a highly fluid, wave-like activation pattern on the cortical surface (reviewed by Muller et al. 2018). Fast oscillations from sensory areas flow toward the frontal, associative regions, whereas direction flow reverses via slow oscillations (Fig. 1b), which recover the DMN. The sensory transmission toward the sensory cortex by fast oscillations and response by slow oscillations was confirmed in humans (Buzsaki et al. 2013) but should be typical in all mammals.

The electromagnetic flows of sensory perception occurring between the limbic system and the cortex form polarity effects (Deli et al. 2018). In rats, high-frequency (40–100 Hz) stimulation of central thalamus relay neurons in vivo caused widespread forebrain activation, but low brain frequency stimulation generated a jerking strain, or convolution (Liu et al. 2015) indicating the strict reliance on incoming stimuli (information).

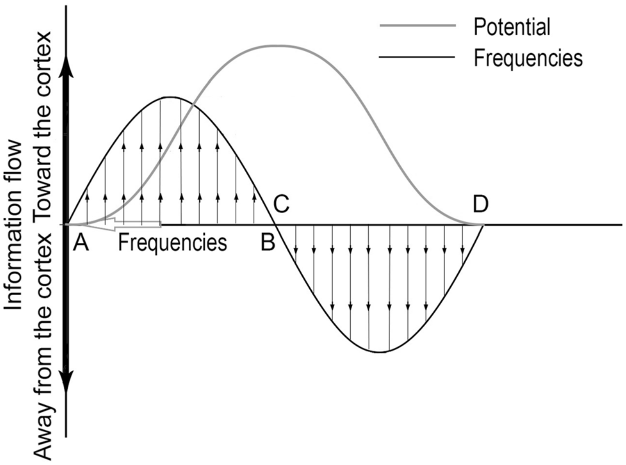

Fig. 1 Changes in energy balance due to the stimulus. The brain frequencies change from high, on the left (A), to low, toward the right (D), determining the direction of information flow in the brain (shown by thin arrows). The resting state of the brain is energy neutral before stimulus (A) and after a response (D). The first part of the cycle (AB) is driven by the stimulus, whereas the evoked potential restores the resting state via self-regulation (CD). The enhanced brain frequencies represent high temperature and robust energy need; the low frequencies expand by forming high amplitude, which correlates to a cooling down Adapted from Deli et al. 2018)

Thermodynamic considerations

According to Landauer's principle, it takes energy to erase one bit of information (Landauer 1961). Let us consider the brain as a computing object. Evoked activities reflect an enhanced 'temperature,' which makes it possible to calculate the thermodynamic cost of neural computation (Fry 2017; Deli et al. 2018; Street 2016). Because goal-directed activities reflect the size of their originating impetus, the characteristic path-length, and the correlation coefficient is proportional to the effort (Kyong et al. 2015) and can approach zero in a randomly organized network (Wu et al. 2012).

Cerebral metabolism depends on a constant supply of both glucose and oxygen. The extensive oxygen use supports steady-state energy metabolism, via neurovascular coupling mechanisms. The subtle Spatio-temporal regulation of the neurovascular coupling might be mediated by neuronal signalling mechanisms (i.e., glial pathways), in addition to sensing energy consumption (Pasley and Freeman 2008). Despite the refined regulation, neurovascular uncoupling and ATP depletion may play a physiological role (Fig. 2, Trevisiol et al. 2017).

Incompatibility with expectations triggers emotions that instigate response that restores the resting state but modifies synaptic organization (i.e., mental energy); state transitions depend on the weighted energy contributions of regions (Betzel et al. 2016; Pop-Jordanova and Pop-Jordanov 2005), see Fig. 1. The evolution of the energy need and synaptic weight of connections leads to memory and learning. The energy need of oscillations (and the resulting mental change) is frequency-dependent. The brain, a voracious consumer of information, is intertwined with the energy/information cycle of the environment.

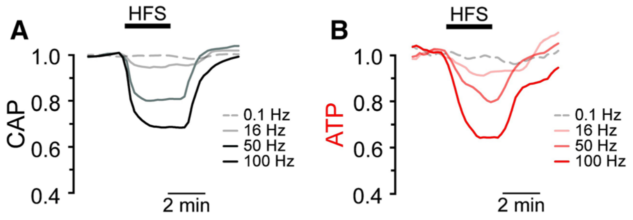

Fig. 2 Compound action potentials (CAP) during high-frequency stimulation (HFS). **a** The CAP area decreases over time during high-frequency stimulation (HFS). The decay amplitude deviates from the absence of HFS, indicated by the dashed line (0.1 Hz, used for normalization to 1.0), and increases progressively with the increase in stimulation frequency (16 Hz, 50 Hz, 100 Hz). **b** Axonal ATP levels also decrease with increasing stimulation frequency, reaching a new steady-state level, which depends on the stimulation frequency (Reproduced from Figure [4] (Trevisiol et al. 2017), eLife, published under the Creative Commons Attribution 4.0 International Public License (CC BY 4.0; https://creativecommons.org/licenses/by/4.0/)

Sensory activation compresses the spatial signal according to an Eigenvalue. Like the musical notes representing a complex musical piece, harmonic brain modes, defined as connectome harmonics, yield the frequency-specific building blocks of cortical activity (Fingelkurts and Fingelkurts 2014; Atasoy et al. 2016). The energy difference between harmonic modes means that it takes energy to switch between emotions. Thus, emotions represent the brain's operating temperature and its intellectual limit. The feelings of autonomy (volition) and competence (mastery) cultivate intrinsic motivation (Deci et al. 1999).

An intelligent response to a stimulus increases future degrees of freedom (Wissner-Gross and Freer 2013), but stress and anxiety reduce it (Rowe and Fitness 2018). An intelligent response to the stimulus corresponds to the mind being an abstract mirror of the environment and adopting the laws of physics.

The resting-state functions as a heat bath. The amount of thermal energy transferred in the Carnot cycle:

$$Q = \int_A^B TdS \tag{1}$$

The efficiency of the Carnot cycle is the amount of work output (η)

$$\eta = \frac{T_2 - T_1}{T_2} \tag{2}$$

where T_2 is the activity (temperature) of the evoked state, and T_1 is the activity (temperature) of the resting state. Energy is lost, and complexity decreases.

The efficiency of the reversed Carnot cycle (η) is the heat removed/the amount of work input

$$\eta = \frac{T_2}{T_1 - T_2} \tag{3}$$

where T_2 is the temperature (activities) of the low frequency of the evoked state of positive emotions, T_1 is the temperature of the resting state. Energy accumulates as the available connection states (complexity).

The role of emotions

A phylogenetic consequence of emotions "allows" mammals and birds to be warm-blooded, or care for their offspring, form the mysterious inner world of consciousness, display impressive learning ability, and develop a nuanced social life. An intelligent response to the incessant stimulus develops the mind into an abstract mirror of the environment. Emotions trigger a response because they represent the fundamental forces of motivation. Emotions have typical brain activity profiles, but based on their energetic profile, only positive and negative emotions exist (active inference framework), which formulate the processing polarities of the brain (Kao et al. 2015). Negative emotions might trigger exothermic processes, which reconstruct the past (Carnot cycle), whereas positive emotions are endothermic processes (reverse Carnot cycle) that control the future and boost mental energy (Deli et al. 2018; Fry 2017), see Fig. 3.

Potentials and electric flows between the cortex and the limbic brain form the evoked cycle that formulates automatic and involuntary energy-information exchange with the environment and inspires the *particle-like stability* of the mind. Because evoked states build on the resting potential, they can be analyzed with the tools of thermodynamics (Deli et al. 2018; Fry 2017). Emotions have a typical brain activity profile but represent only positive or negative states based on their energy use. The central tenet here is that by considering mental energy as an analog to potential energy in physics, the Carnot cycle can model the brain's operation.

Physical processes can be dissipative, which reconstructs the past, and intelligent, those that anticipate the future (Cox 1979). The first kind, exothermic process dumps entropy, and energy into its environment, whereas the latter, endothermic actions absorb entropy while

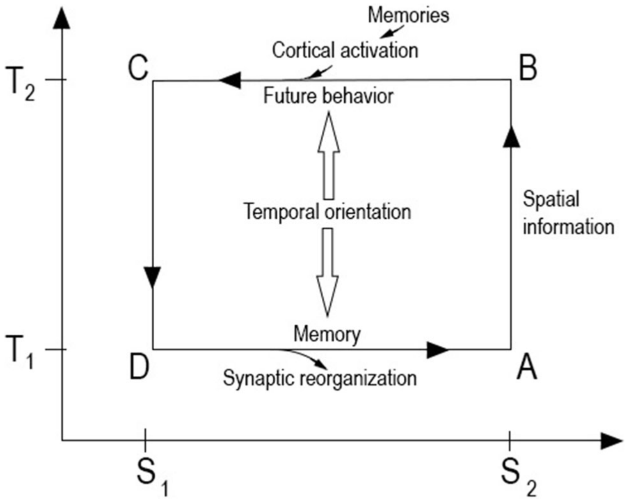

Fig. 3 The reversed Carnot cycle illustrated on a temperature-entropy plane. The cycle operates via self-regulation between the high frequency, evoked state (T2), and the resting state (T1); the horizontal axis represents entropy. Stimulus increases the frequencies during the compression phase (**AB**). The energy state of synaptic potentials permits the electric flow to spread through the cortex (**BC**). The resulting potential reverses the direction of the electric flow (**CD**); these slower oscillations expand to formulate a response. Synaptic reorganization accumulates complexity as memory. Synaptic changes prepare the neural system to better respond to stimuli in the future (**DA**). The electrical activities reformulate the high entropy, resting state (**DA**). In deep learning, computation depends on the depth and number of connections of the network, and the phases of information processing are very similar to the cycle of neural computation

requiring energy to operate. The thermodynamic computation by a cortical neuron provides an example of the second possibility. Fry analyzed the thermodynamics of action potentials generated by one neuron (Fry 2017). 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 role of energy in cognition (Deli et al. 2018).

We examine the Carnot cycles. The thermodynamic considerations of positive and negative emotional states as they relate to mental effort and mental energy can answer the crucial questions in psychology and aid AI research.

Positive emotions: the reversed Carnot cycle

The ability to form an intelligent response to a stimulus depends on the flexibility and complexity of the resting brain. In diverse cortical areas, spike frequency depends on both the environmental inputs and internal conditions (Mildner and Tamir 2019; Piscopo et al. 2018). In other words, the history and current state of the system are just as crucial in determining the quality of neuronal activation as the stimulus itself. Consequently, the state of the brain, i.e., the observer, determines the information value of the stimulus.

High mental plasticity inspires exploration for its own sake, as a goal in itself (DeYoung 2013). The willingness to work hard for rewards, even in cases of the low probability of payout, is the function of mental energy (Di Domenico and Ryan 2017; Treadway et al. 2012). Mental energy is synaptic flexibility that reflects higher degrees of freedom, manifested as trust and confidence (Ryan et al. 2016). Self–confidence encourages a can-do attitude that builds upon the robust and satisfying mental state. Mental energy deflects negativity and conflict, inspiring creativity, success, and even longevity (Inzlicht et al. 2018; Kaczmarek et al. 2017; Stellar et al. 2015; Diener and Chan 2011; Aknin et al. 2012; Steptoe and Wardle 2005; Ryan and Deci 2017).

Intrinsic motivation has been attributed mostly to the dopaminergic systems (Gottlieb and Oudeyer 2018; Grolnick and Ryan 1987; Kobayashi and Hsu 2019; Treadway et al. 2012; Salamone and Correa 2012). It inspires natural curiosity and interest, to seek out challenges, and to develop and advance the self (Di Domenico and Ryan 2017; Panksepp 1998). Intrinsic motivation is an energetic, powerful state that is associated with better physical and mental health (Boehm and Lyubomirsky 2008; Csikszentmihalyi and Hunter 2003; Diener and Chan 2011; Koivumaa-Honkanen et al. 2004).

Recent neuroimaging data suggest that anterior mid-cingulate cortex (aMCC) connectivity plays a crucial role in volition and can indicate grit, persistence, and better academic performance (Touroutoglou et al. 2019). Higher levels of energy productions correlate positively with better performance, even in animals (Biro and Stamps 2008; Careau and Garland 2012). High performers in intelligence tasks showed lower brain activations, indicating higher neural efficiency (Haier et al. 1988; Poldrack 2015) accompanied by slower oscillations (Bethell et al. 2012; Seo et al. 2008), which in turn expand time perception (Neupert and Allaire 2012; Remmers and Zander 2018a, b).

The resulting negative temporal curvatures correlate with increasing temporal dimensionality (Tozzi et al. 2017, Tozzi and Peters 2017; see also Table 1), as well as neurotransmitter action, such as dopamine (Soares et al. 2016; Fredrickson and Joiner 2002; Rudd et al. 2012; Peters et al. 2017). For example, being in the present moment or experiencing awe, trust, and belief correlate with the sense of temporal excess (Csikszentmihalyi and Hunter 2003; Neupert and Allaire 2012; Rudd et al. 2012). The subjective sense about the wealth of time provides a calm disposition, which inspires better decision-making (Mitchell et al. 2018). Higher degrees of freedom also enable intelligent responses.

The enthusiasm and energy that characterize awe and other positive emotions reflect an information-free state. Because low frequencies lack details (Figs. 3 and 4) and engage in more broad cortical areas, they inspire associative representations (Kounios and Beeman 2009; Machado and Cantilino 2016). The slower oscillations can access to a high number of microstates, to produce almost any thought. The temporal variability of the resting-state connectivity, i.e., high entropy, correlates with fluid intelligence (Yang et al. 2019). These endothermic processes control the future by enhancing intellect (Fry 2017; Wissner-Gross and Freer 2013).

Similarly, low-frequency brain stimulation boosts creativity (Lustenberger et al. 2015), which increases synaptic complexity and future freedom of action. Likewise, low-frequency optogenetic stimulation of the anterior cingulate areas decreased anxiety in mice (Kiefer and Pulvermüller 2012). Mindfulness meditation training, for example, is an energy-requiring slowing down that can reverse negative attitudes (Fig. 4, for explanation). Boosting mental energy this way may improve synaptic complexity and mental flexibility.

In summary, the energy frugal slow oscillations correlate with a flexible and dynamic synaptic map of an energetic mental state, and this can be modeled by the reversed Carnot cycle. Landauer’s principle shows that creativity, acceptance, and flow must be information-free conditions (Fig. 4, top). Endothermic processes control the future (enhance mental energy), and exothermic processes

Table 1 The physiological consequences of different brain states

	Reversed Carnot cycle High entropy resting state	Carnot cycle Low entropy resting state
Mental state	Positive emotions	Negative emotions
Frequencies	Slow oscillations expand—information poor	High frequencies contract—detail-oriented, accumulate information
Temporal dimensionality	Positive temporal curvature—lower dimensionality	Negative temporal curvature—higher dimensionality
Subjective sense of time	Time perception expand (the luxury of time inspires confidence)	Time perception expands (details overwhelm with stress)
Future degrees of freedom	Degrees of freedom enhances	Degrees of freedom reduces
Thermodynamic consequences	An endothermic cycle absorbs energy and entropy from the environment	An exothermic cycle dumps energy and entropy onto the environment
Consequences for the organism	High mental energy (intellect)	Degradation of mental energy → mental and immune problems

The thermodynamic and psychological consequences of basic emotions

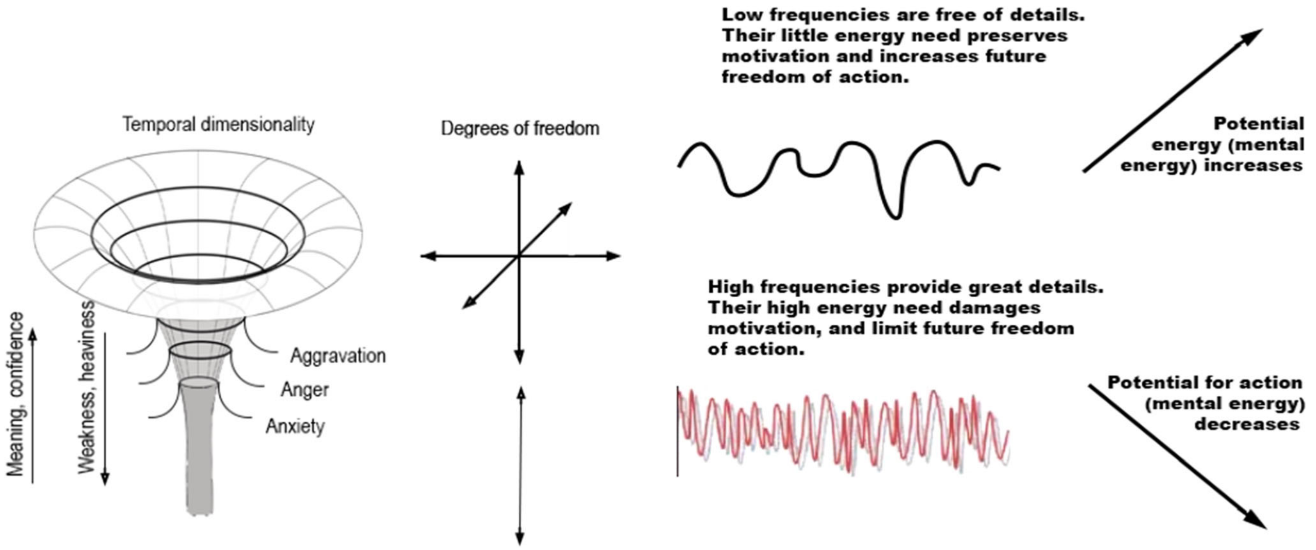

Fig. 4 The relationship between emotions and mental energy (future freedom of action). **a** Mental energy permits positive emotions and meaning that expand the future freedom of action (top). The process, such as acceptance, learning, and meditation, requires energy. The higher energy needs of aggravation, anger, and anxiety constitute stress, which urges decisions that decrease the future freedom of action (Adopted from, Deli 2020). **b** Low frequencies leave the brain energy resources intact, allowing a sense of energy and enthusiasm. (top) High-frequency oscillations confuse with overwhelming details; their high energy need triggers an immune reaction, sows uncertainty, and impatience that corrupt mental freedom

reconstruct the past by degrading mental energy (Deli et al. 2018; Fry 2017), see Fig. 3. Positive emotional states not only feel powerful but represent more energetic conditions, the so-called mental energy. The energy from the environment fuels the endothermic process, underlining the observation that mental energy is a social characteristic and evolves closely intertwined with the surrounding. The endothermic cycle is the source of intellect and should be the objective of all education.

In Eastern beliefs, equanimity is a state of acceptance (i.e., absorbing energy). High intellect is an energetic state that can produce a full range of emotions and permits better control of the future (Deli et al. 2018). Learning and various spiritual practices, such as meditation, acceptance, and gratitude, which boost creativity, happiness, and wisdom, can reformulate the mind.

Negative emotional states: the Carnot cycle

Mental energy ensures emotional stability and permits a focus on long-term goals. Its lack degrades perseverance. The resulting impulsiveness thwarts people's feelings of autonomy (volition), competence (mastery) (Deci et al. 1999), and intrinsic motivation. We will examine the negative mind in comparison to positive emotions.

Energetic consideration (Erosion of mental energy)

Negative emotional states have more significant energy requirements than positive emotional or neutral mental states (Joffily and Coricelli 2013; Saarimäki et al. 2015, 2016; Saarimäki 2017). The preponderance of negative emotions parallels high-frequency limbic activity and decreased prefrontal functioning (Seo et al. 2008). The detailed and deterministic oscillations waste energy, narrow focus, and reduce temporal dimensionality. Enhanced brain frequencies may trigger long-term potentiation (Bliss and Lømo 1973), which increases the likelihood of activating the same synaptic path. Stress and anxiety reduce the degrees of freedom (Rowe and Fitness 2018), blinding people for the possibilities open to them, see Table 1 and Fig. 4, bottom (Lupien et al. 2007).

High-frequency brain waves produce a constricted feeling and increase time perception (Fredrickson and Joiner 2002; Yamada and Kawabe 2011; Peters et al. 2017) even for unconscious stimuli (Oei et al. 2012). Rumination, regret, and remorse waste mental resources and degrade the ability to carry out intentions (Joffily and Coricelli 2013). The preoccupation with the past is an indication of compromised mental energy and information accumulation. Due to the higher energy need of all negative emotions, highly anxious individuals must exert considerably more cognitive effort (Joffily and Coricelli 2013; Saarimäki et al. 2015, 2016; Saarimäki 2017), which exhausts motivation (Trevisiol et al. 2017), see Fig. 2. In anxious individuals (Moran et al. 2015), decreased theta band synchrony typically produces task-irrelevant signals and inferior post-error behavior (Inzlicht et al. 2015). Insecure and guilty people perceive themselves as heavier and their chores more burdensome (Day and Bobocel 2013).

Intolerance of uncertainty (e.g., generalized anxiety disorder), impulsivity enhances the propensity to develop problems with alcohol, drugs, gambling, overspending, and overeating (Hamilton et al. 2015; London 2016). In humans, recurring automatic thought patterns of revenge thinking, regret, or remorse represent insecurity that increases the likelihood of contradiction, critical tendency, aggravation, or complete withdrawal. Over the long-term, the adverse effects curtail freedom and induce vulnerability to immune problems and mental diseases (Gehring et al. 2018; Stanghellini et al. 2016). Immune challenges further impair social behavior by altering neuro-immune signaling in brain regions important for reward/motivation.

Anxiety and depression represent energy-poor states (Wise et al. 2017). In recent rodent's experiments, repeated stress exposure, which reduced plasticity by corrupting connectivity within the medial PFC, drove depressive behavior (Li et al. 2018; Yang et al. 2018). The stagnation of vital processes and an incapacitating slackening the flow of time characterize depression (Stanghellini et al. 2016). The reduced motivation in depression can be addressed by dopamine and norepinephrine (Loy et al. 2018), for example, catechol-O-methyltransferase (COMT) inhibitor tolcapone increases dopamine tone in the frontal cortex (Mitchell et al. 2018) indicating the lack of sufficient mental energy.

Finally, the degradation of mental energy and performance might be the first symptom of mental diseases. Neurodegeneration in areas critical for memory, such as the medial temporal lobes, the entorhinal cortex, and the hippocampus, might be the precursor for various forms of dementia. For example, the compromised integrity of medial frontal regions (Apostolova et al. 2007) might lead to apathy in Alzheimer's disease (AD, Drago et al. 2010; Kumfor et al. 2018; Nobis and Husain 2018). Other studies found a relationship between the lack of mental energy and apathy (Patzelt et al. 2019) in AD (Perri et al. 2018) and other conditions. The "impairment of intrinsic motivation is one of the characteristics of schizophrenia" (Takeda et al. 2018), Parkinson's disease (Muhammed et al. 2016), neurodegenerative diseases such as frontotemporal dementia (Bertoux et al. 2015; Mitchell et al. 2018) and other clinically-related traits (e.g., anhedonia and apathy) (Patzelt et al. 2019).

Resting entropy

A high signal complexity, particularly in the DMN, is essential for cognitive functionality (Grieder et al. 2018; Sokunbi et al. 2013). All negative emotional states degrade the entropy of the DMN (Low et al. 2018; Saxe et al. 2018). DMN disruptions and reduced resting-state entropy have been reported in schizophrenia spectrum disorder (Smith et al. 2018), depression (Wise et al. 2017), autism (Padmanabhan et al. 2017; Hogeveen et al. 2018), and AD (Jones et al. 2011; Gray and Thompson 2004; Wang et al. 2017). Altered entropy in AD indicates a disturbance of both local information processing and information transfer between distal areas. Specifically, the entropy decrease correlates with the progression of AD (Grieder et al. 2018).

As mentioned earlier, the reduction of entropy in negative emotions is an exothermic condition, which damages emotional regulation and intellect. Mental damage might occur as a consequence of the unsustainable accumulation of information. In other words, the extended effort to process information overwhelms the hormonal system and deteriorates into immune and mental problems.

Antipsychotic medications that successfully ameliorate the negative symptoms of schizophrenia (delusions, hallucinations, and others) have been available for some time; however, they leave patients with residual symptoms, of which lack of motivation is the primary driver of poor outcome and low quality of life (Kiang et al. 2003). Problems with motivation and particularly the corruption of mental energy might lead to dramatic differences in health outcomes, intellectual, and social performance (D'Acquisto 2017; Kopec et al. 2019; Sizemore et al. 2018).

In major depression, the less variable resting-state functional connectivity leads to repetitive thought patterns (Charney 2016; Kaiser et al. 2016; Murrough et al. 2016), indicating a lack of freedom. It is suspected that antidepressants ameliorate the deficits in synaptic plasticity (Abdallah et al. 2015). Tolcapone, a catechol-O-methyltransferase (COMT) inhibitor, may reduce impulsivity (Mitchell et al. 2018). Although stroke lesions are restricted to one hemisphere, entropy reduction extends to nodes from the contralesional hemisphere (Bastos et al. 2014), indicating the unity of the mind and the global nature if entropy in underpinning mental changes.

Time perception

Stress distorts time perception, which causes "the nonspecific response of the body to any demand upon it" (Selye 1974) and a loss of control. The impaired time perception (Mitchell et al. 2018) shows a close relationship with emotion regulation and correlates with some clinical conditions, involving problems in decision making. Conflict inherently enhances the neural activity and triggers a negative mindset, a state more prone to activation; worried people fail to produce the connectivity for theta phase synchrony (Cavanagh and Frank 2014) between medial and lateral sites (Moran et al. 2015). The lack of freedom leads to a compromised response such as aggravation, and the fight or flight response (Verma et al. 2011). For example, prisons enhance impulsiveness, which reducing emotional coloring and trust, thereby inspires criminal personalities (Meijers et al. 2018) and addictions (Hamilton et al. 2015; London 2016) (Fig. 4, bottom).

The connection of slower oscillations with positive emotions and enhanced brain frequencies with negative mental states has been corroborated in numerous studies (Bethell et al. 2012; Seo et al. 2008). The bottom line is that low frequencies form negative, whereas negative emotions form positive temporal curvatures with increasing and decreasing temporal dimensionality modifications, respectively (Tozzi et al. 2017). Importantly, in both instances, time perception expands (Neupert and Allaire 2012; Remmers and Zander 2018a, b). Tolcapone, catechol-O-methyltransferase (COMT) inhibitor, may reduce impulsive decision-making and lessen the distorted time perception via dopamine effects (Mitchell et al. 2018).

Emotional flatness

As discussed above, emotional problems are often the primary symptoms in mental disease and immune disruptions. Because the intellect is related to the production of an expansive range of emotions, mental decline correlates with the greying of emotions (Meijers et al. 2018). AD patients evaluate the pleasant images as less pleasant, the negative scenes as less disturbing, and prosody recognition is also impaired (Amlerova et al. 2017). An emotional flatness, deficits in emotional memory, and an inability to overcome prepotent response tendencies are often seen in patients with frontotemporal dementia (FTD) and AD (Chen et al. 2017). Lower brain signal complexity is also associated with a higher degree of cognitive decline (Grieder et al. 2018; Li et al. 2018) and AD-related pathology.

Even without structural atrophy and with typical performance on cognitive tests, amyloid-positive AD patients have higher global connectivity within the right anterior insula and superior temporal sulcus (STS). Entropic changes due to hyper-connectivity might represent *pre-symptomatic* indicators of the disease, causing mental and emotional rigidity (lower degrees of freedom) (Fig. 4, bottom). Indeed, increased reactivity and negativity, even at a single time-point, increase the risk of late-onset AD (Fredericks et al. 2018). The temporal anti-correlation between task-positive (i.e., functional networks during task execution) and the task-negative RSNs (i.e., DMN), typically found in healthy subjects, is attenuated in progressed stages of AD Grieder et al. 2018).

Hyper-connectivity degrades cognitive flexibility. Hyper-connectivity of the superior temporal sulcus (STS), a brain region that plays crucial roles in social processing, is associated with lower interpersonal warmth and a trend toward increasing emotional reactivity (Fredericks et al. 2018). Recent results have indicated that reduced temporal dimensionality and structural connectomics might be behind problems of emotional regulation (Sizemore et al. 2018; Tozzi and Peters 2017). The above energetic considerations lend further support to the possible dimensionality changes.

The emerging rule is that the loss of mental energy precedes emotional flatness; corrupted cognitive functioning (Sapey-Triomphe et al. 2015; Bourgin et al. 2018) is concerned with the past, which engenders insecurity. The process must be modeled by the Carnot cycle, where mental degradation is connected to lower resting entropy. Negative states are exothermic processes that dump energy onto the environment via aggravation, rumination, and critical tendency. Over the long-term, the loss of complexity, i.e., functional and synaptic changes, corrupts intellect and leads to anatomically detectable problems. Recognizing the role of thermodynamic changes in stress and anxiety might inspire novel treatments for mental diseases.

Conclusions

Traditionally, neuroscience, which studies the brain, and psychology, which studies the mind, sharply differed in their methodologies and objectives. Synthesizing their insights into the cohesive framework of consciousness is the intriguing challenge of our time. This review has attempted to connect the energy metabolism of the neural system with psychology and intellect based on the FMH.

The brain's recurrent energy-information exchange via stimulus places it within the thermodynamic cycle of the environment and allows the examination of the brain based on information and energy. Intelligent systems are sensitive to changes in the environment. Meaningful perception is an abstract representation of the physical world.

Incoming information induces electric flows resulting in minute potential differences that modify the global (brain-wide) synaptic map. Thus, synaptic organization and complexity, which represent an energy potential of memory and learning, formulate the basis of future behavior. As material systems observe the principle of least action when moving in space, intelligent systems optimize their action repertoire between the past and the future. The temporal equivalent of the stationary action in physics is a minimum energy configuration toward the future.

We have shown that basic physical and information-theoretic principles can describe intelligent computation. Establishing the thermodynamic basis of intellect can inspire educational and social reforms. High intellect is an energetic state that can produce a full range of emotions. Mental energy is so intertwined with the immune and hormonal functions that erosion of mental energy causes mental problems and increases the vulnerability to diseases. Verifying the thermodynamic underpinning of mental changes could revolutionize psychological and social sciences.

The above findings corroborate the recent findings by respected laboratories on consciousness; intellect correlates with increasing resting entropy, and compromises of mental energy compromise intellectual performance, lead to mental diseases and immune problems. Emotions can be considered the fundamental forces of the mind, which inspire interaction and mental change. Mindfulness, learning, meditation, gratitude, and other mental practices might improve well-being by increasing mental freedom of action. The highest productivity of the brain results from turning challenges into positive emotional states and reversing mental degradation via learning and various spiritual practices.

The neural system performs computations with thermodynamic efficiency in orders of magnitude higher than current supercomputers. Our improving intuition about intelligent computations will allow the development of novel techniques and applications in the rapidly changing field of thermodynamics, AI, and robotics.

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Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest.

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