New Ideas in Psychology 79 (2025) 101188

Contents lists available at ScienceDirect

New Ideas in Psychology

journal homepage: www.elsevier.com/locate/newideapsych

Feeling the Heat: A Thermodynamic Perspective on Emotions, Motivation, and Time Perception

Eva Déli[a,*], Felix Schoeller[b,c], Adam Safron[b,d], Abhinandan Jain[c], Arturo Tozzi[e], Vladimir Adrien[f,g], Nicco Reggente[b]

[a] University of Debrecen, Faculty of Health Sciences, Department of Psychology, Debrecen, Hungary
[b] Institute for Advanced Consciousness Studies, Santa Monica, CA, USA
[c] MIT Media Lab, Cambridge, MA, USA
[d] Allen Discovery Center, Tufts Univ, Medford, MA, USA
[e] Dept of Physics, University of North Texas, Denton, USA
[f] Université Sorbonne Paris Nord, Department of Infectious and Tropical Diseases, Avicenne Hospital, AP-HP, F-93000, Bobigny, France
[g] Université Paris Cité, Inserm UMR-S 1266, Institute of Psychiatry and Neuroscience of Paris (IPNP), Paris, 75014, France

ARTICLE INFO

Keywords:
Emotions
Motivation
Time perception
Thermodynamics
Energy regulation
Entropy
Body temperature
Binary regulation

ABSTRACT

We are introducing a novel thermodynamic model of emotion. In this model, emotions are regarded as deviations from equilibrium, akin to fluctuations in body temperature. This bipolar regulation maintains bodily and psychological homeostasis while spurring mental development. Emotional regulation typically occurs through expanding one's perception of time. Positive, low-information content emotions can reduce action drive, but stressful, information-rich conditions can heighten it. Therefore, time perception can potentiate the capacity of emotions to motivate. However, time perception accelerates to facilitate fluid action performance, with the state of flow representing a unique state of contentment and challenge. By anchoring psychological processes to the principles of energy and entropy, our model offers a comprehensive bipolar foundation for understanding motivation and behavior. Beyond its theoretical implications, this model also lays the groundwork for addressing mental health conditions resulting from the dysregulation of emotions. It can inspire potential interventions to harness the mind-body connections elucidated by our thermodynamic perspective.

1. Introduction

The global rise in stress disorders highlights the urgent need to understand emotional resilience and its role in the development of mental diseases (Nestler & Russo, 2024). Traditional approaches have treated emotions as separate domains, failing to capture their intricate interdependencies. For example, cognitive theories have focused primarily on the mental processes underlying emotions (Barrett, 2017). At the same time, physiological research has investigated bodily responses, such as heart rate and facial expressions, largely independently of motivational and subjective factors. This compartmentalized view has limited our ability to explain the complex relationships and paradoxes observed across these realms of human experience. Understanding how emotions relate to subjective experiences (i.e., feelings), motivation, and disease progression has remained elusive.

This article proposes a novel thermodynamic model that integrates emotions, motivation, and associated physiological mechanisms within a unified framework. The brain keeps bodily and psychological equilibrium by intertwining every regulatory system with emotions. Nevertheless, the multifaceted nature of the relationship encourages further study. This work examines how emotions serve temperature regulation and psychological homeostasis. By conceptualizing the brain's functioning through thermodynamic principles of energy and entropy, we offer a cohesive perspective to resolve longstanding questions and paradoxes surrounding these interrelated processes.

1.1. *Thermo-emotional covariations from a thermodynamic lens*

Experimental research confirms the phylogenetically ancient relationship between emotions and temperature regulation across various species, including reptiles, foxes, pigs, rabbits, rats, mice, and humans (Briese, 1995; Briese & Cabanac, 1991; Cabanac, 1999; Frosini et al.,

* Corresponding author.
E-mail address: deli.eva@etk.unideb.hu (E. Déli).

https://doi.org/10.1016/j.newideapsych.2025.101188
Received 5 August 2024; Received in revised form 26 July 2025; Accepted 4 August 2025
Available online 11 August 2025
0732-118X/

2000; Groenink et al., 1995; Moe & Bakken, 1997; Parrott et al., 1995; Terlouw et al., 1996; van der Heyden et al., 1997). Although thermoregulation exists to some degree in most animals, the endothermic phenotype—characteristic of humans and other mammals—depends on complex metabolic networks and multiple internal feedback loops (Grigg et al., 2021; Seebacher, 2020). For example, embryo incubation drives the evolution of endothermy (Farmer, 2020), which is phylogenetically predicated on thermoregulation (Clavijo-Baque & Bozinovic, 2012). Endotherms maintain a stable core temperature with the aid of crucial mechanisms, including vasoconstriction, shivering, and sweating (Madden & Morrison, 2019; Nowack et al., 2017). The brain's high energy use ensures optimal information processing while maintaining physical and psychological equilibrium (Dempsey et al., 2022; Huang, Zhang, Wu, Mashour, & Hudetz, 2020). Thermal control is a vital component of an overarching regulatory system, exerting downstream effects on action motivation and behavioral adaptations (Inagaki et al., 2019; Kataoka et al., 2020; Nashiro, Min, & Yoo, 2022).

Physical or mental instability prompts a wide range of protective mechanisms. Emotions are paramount in this regulatory hierarchy as they intertwine with other regulatory processes. Moreover, the distinct physiological signatures of emotions represent specific energy configurations of the brain (Hesp et al., 2021; Kao et al., 2015; Sadowski et al., 2020), and, like temperature, they oscillate around a neutral position, forming an emotional set-point (Northoff & Tumati, 2019). Recent work utilizes temperature as a means of characterizing emotions (Escobar et al., 2020). Contentment promotes rest and recovery (Brown & Thorsteinsson, 2020) by reducing metabolic rate and body temperature, thereby conserving energy through parasympathetic restorative processes (Seebacher, 2009). In contrast, stress is a highly demanding condition (Keller et al., 2019; Meeusen, Van Cutsem, & Roelands, 2020), where noradrenaline initiates the fight-or-flight response within seconds (O'Connor, Thayer, & Vedhara, 2020). Furthermore, the varied effects of stress depend on personal, environmental, and other situational factors. However, its adverse health effects in anxiety, dissociation in trauma, or even depression (Comtesse et al., 2019; Mason et al., 2024) warrant a deeper thermodynamic investigation.

Emotional expressions are fundamentally linked to physiological changes regulated by the autonomic nervous system. At the same time, their feedback representation reflects motivational aspects (Quadt et al., 2022). Moreover, emotion and temperature may be under thermodynamic control (Déli and Kisvarday, 2020; Grigg et al., 2021; Seebacher, 2020). This perspective posits that the brain's mechanisms for heat and work transfer play a crucial role in regulating emotional states, and conversely, that emotional states can influence thermoregulation. In support of this, psychological stress, known to elevate blood pressure, heart rate, and heart function—even during sleep (Hall et al., 2004)—increases core temperature, a phenomenon referred to as psychogenic fever (Oka et al., 2001). This psychogenic fever results from a temporary elevation in the thermoregulatory set point, mediated by both prostaglandin E2-dependent and independent mechanisms (An & Kim, 2011; Fossat et al., 2015; Kluger et al., 1987; Morimoto et al., 1991).

Heat stress can lead to impulsivity (Fredericks et al., 2018; Wittmann & Paulus, 2008; Paasche et al., 2019), drug-seeking behavior, and criminal activity (Corcoran & Zahnow, 2022). Inversely, fear triggers thermoregulation disturbances in substance abusers (Lowry et al., 2009; Raison et al., 2015). People with depression have higher body temperatures (Mason et al., 2024), and median raphe stimulation, which affects temperature regulation, can produce depressive-like behaviors (Fazekas et al., 2021). These and other findings suggest a neurological link between emotion and temperature (WILLIAMS & Bargh, 2008). To gain a deeper understanding of this relationship, we explore the mechanisms of thermodynamic regulation in more detail.

1.2. Variations of time judgment

Understanding the mechanisms underlying time perception requires distinguishing between different types of temporal judgments. A key theoretical distinction exists between the perceptions of short durations (e.g., milliseconds to seconds), typically measured through reproduction or estimation tasks and the subjective awareness of time's passage often referred to as passage-of-time (PoT) judgments. These two aspects are functionally dissociable: while short-duration judgments are closely linked to internal pacemaker mechanisms and are modulated by arousal and attention (Gibbon et al., 1984; Wittmann, 2009), PoT judgments rely more on self-reflective and interoceptive processes, such as emotional state and bodily awareness (Droit-Volet, & Fayolle, 2024; Martinelli & Droit-Volet, 2022).

Incorporating this distinction into our thermodynamic framework, we conceptualize duration estimation as a dynamic process modulated by arousal-driven shifts in entropy and energy. High-arousal states, whether positively or negatively valenced, have been shown to accelerate internal clock processes, resulting in time overestimation (Cui et al., 2023). An expansion of subjective time is useful for decision-making, while contraction of subjective time drives action (D'Agostino et al., 2023). In contrast, low-arousal emotions, including contentment or mild joy, do not produce consistent distortions in short-duration estimates. These findings challenge earlier claims of a general "positivity effect" on temporal expansion and underscore the primacy of arousal, rather than valence, in modulating temporal metrics.

Moreover, our model emphasizes that PoT judgments, i.e., feelings that time is dragging or flying, are not reducible to clock-speed effects. Instead, they emerge from higher-order awareness of emotional and cognitive change (Wittmann, 2015). For instance, the emotion of awe leads to underestimation of duration in attention-based timing tasks, likely due to perceptual overload (Droit-Volet et al., 2024). Simultaneously, awe may induce a metacognitive experience of timelessness, a distinct subjective effect more closely tied to interoceptive processes and self-transcendence. We propose to map these dual effects thermodynamically: attentional overload decreases timing accuracy, while self-transcendent states can stabilize entropy.

Early work investigated the effect of increases in body temperature on time estimates (Hoagland, 1933). Increases in body temperature shortened the intervals produced, but lengthened duration estimates (Francois, 1927; Wearden & Penton-Voak, 1995). More recent studies support the stress-induced slowing of time perception (Ogden et al., 2019); however, the repeated anticipation of holidays can actually speed up time perception (Ogden et al., 2024).

To situate our approach within broader theoretical debates, we briefly compare our framework with several established models of time perception. The dual klepsydra model (Wackermann & Ehm, 2006) posits that interval timing arises from the gradual discharge of a leaky integrator, an analogy to fluid flowing through a clepsydra or water clock. In contrast, the DOIT (Dynamic Occupation in Time) model examines how the experience of time varies based on the qualities of activities and their context (Larson, 2004). Although our model differs in its thermodynamic formulation, these approaches recognize the irreversibility of time and the influence of dissipative processes.

Physical movement across species and tasks hastens time perception, improving timing accuracy (Robbe, 2023). The time perception rate is greatest in flow, a unique state where the balance of action, motivation, and confidence optimizes performance through spontaneous, coherent action flow (Failing & Theeuwes, 2016; Rutrecht, Wittmann, Khoshnoud, & Igarzábal, 2021). Similarly, Csikszentmihalyi's flow model describes the distortion of time during immersive tasks, wherein attentional focus and action-feedback loops yield an altered experience of time (Csikszentmihalyi, 1990). Our thermodynamic view reframes this by suggesting that flow arises at an equilibrium point between arousal (energy) and confidence (stability), facilitating seamless temporal integration.

As physical time is relative to spatial motion, psychological time is also relative to imaginary motion (Allingham et al., 2021; Spapé et al., 2021). Imagining accelerating movement resulted in a relative overestimation of time, or time dilation, while decelerating movement elicited a relative underestimation, or time compression (Hallez et al., 2023). Our model posits that perceived time is regulated by energetic and informational constraints, offering a physicalist grounding through entropy and thermoregulation.

1.3. The role of entropy

Thermodynamic regulation is crucial for efficient brain functioning. Because the energy needs of neurons during intrinsic activities are orders of magnitude larger than during stimulation for all levels of cognition (de Lara, 2020; Raichle, 2010), rapid shifts from the brain's high-dimensional resting state to lower-dimensional evoked activities (Singer, 2021) facilitate optimal information transfer. Nevertheless, stable intrinsic activities expedite spontaneous recovery of the resting state. In this simplified view, intellect generation is based on information exchange with the external environment (Ahissar & Assa, 2016; Déli et al., 2017; Llinás and Paré, 1996; Northoff, 2018), with sensory and motor processing forming a thermodynamic cycle.

Renyi's informational entropy generalizes entropy by forming scalar exponent alpha (Jizba & Arimitsu, 2001). Baez (2011) demonstrated a direct relationship between Renyi's exponent alpha and inverse temperature beta (i.e., coldness). Intelligent information processing often involves a type of information erasure, inducing a sense of "coldness" while increasing overall neural organization (O'Neill and Schoth, 2022).

Rényi and Shannon's informational entropy can describe psychological and cognitive states, and predict task performance and mental well-being (Ince et al., 2017; Shannon, 1993). For instance, higher variability at rest (i.e., high entropic states) correlates with fluid intelligence (Wang et al., 2018; Yang et al., 2019) and openness (Zmigrod et al., 2019), but decreases in brain entropy are seen in compromised states of consciousness (Varley et al., 2020). For example, stress is analogous to time pressure, the inability to cope with the pace or intensity of sensory influx (Déli et al., 2018, 2021, 2022), demonstrating emotions' interconnection with the brain's energy and information processing. The following section will proceed to a discussion of time perception in motivation.

1.4. The thermodynamics of time perception

Studies on behavioral activation systems have revealed overestimation bias scores for both positive (Lehockey et al., 2018; Simen & Matell, 2016; van Hedger et al., 2017) and stress-inducing situations (Remmers & Zander, 2018; Wise et al., 2017). For instance, novel stimuli or rewards can dilate time perception through what is known as the 'oddball effect' (Failing & Theeuwes, 2016; Ma et al., 2024), with surprising or emotionally charged moments feeling as if time 'froze.' A similar sense of permanence occurs during stress (Hollis et al., 2015; Robbe, 2023). However, the psychology of these experiences contrasts dramatically. In a stressful context, dilated time perception evokes an unbearable sense of permanence, which triggers desperate escape behavior through impatience and sympathetic arousal (Gladhill et al., 2022; Hosseini Houripasand et al., 2023).

The dilation of time perception in both positive and negative states correlates with emotional intensity (Biderman et al., 2020; Déli & Kisvarday, 2020; Zanin et al., 2019), hinting at an underlying energy relationship (Toso et al., 2020). We want to note that some studies suggest that positive emotions do not influence time perception (Ogden et al., 2019). However, drug-induced expansion of time perception is indeed linked to elation. This correlation is significant as it suggests that the sense of spaciousness experienced during elation can lead to mental expansion, potentially giving rise to new ideas and creative insights (Green, Kavanagh, & Young, 2003). These findings underscore the connection between the expansion of time perception and elation, whether drug induced or arising from positive states.

Due to its mental energy boosting ability, musicians and artists have turned to cannabis to enhance creativity, supporting our original claim (Kowal et al., 2015). Moreover, the most pronounced alterations in time perception occur during emotional polarities, such as awe (Rudd et al., 2012) and depression (Stanghellini et al., 2016; Thönes & Oberfeld, 2015), when time appears to stand still (Fig. 1). These results inspired some scientists to suggest that depression is analogous to a positive spacetime curvature, even a black hole state (Déli, 2024; Kent, 2023).

The connection between emotions and energy is also evident in the fact that the perception of time slows down more significantly during the transition to negative states than during the states themselves (Gable & Poole, 2012; Wang & Lapate, 2024). Likewise, the cognitive challenge of withdrawal (Di Lernia et al., 2018; Gable et al., 2022) and sleep deprivation (Şen et al., 2023) dilate time perception. Our argument defines time perception as an even function, represented by a graph that remains unchanged under reflection in the y-axis (Fig. 1). Interestingly, our time perception curve is analogous to the upside-down U-shaped curve of the Yerkes-Dodson law, which relates performance to circulating levels of stress hormones (Beerendonk et al., 2024; Yerkes & Dodson, 1908; Lupien, Maheu, Mt, Fiocco, & Schramek, 2007). This similarity underscores the thermodynamic foundation of emotions' potential for motivation.

An intriguing question remains of why diverse experiences – from intense states of anxiety to the calmness inspired by awe or nature – dilate time perception (Bannister & Eerola, 2021; Davydenko & Peetz, 2017; Failing & Theeuwes, 2016; Mitchell et al., 2015; Rudd et al., 2012). For example, information overload during stressful states can cause difficulty concentrating and purposeful behavior (Nutt, 1999). Anxious people usually resort to impulsivity and meaningless, arbitrary actions until action motivation is halted in depression (Stanghellini et al., 2016; Wittmann & Paulus, 2008), implying an inverse relationship between mental adversity and the ability to change it.

In contrast, the low action motivation of positive mental states indicates energy frugality, which may explain their connection to parasympathetic restorative processes in long-term psychological well-being (Table I). A muted action motivation might represent some form of minimum energy path, analogous to the principle of stationary action in physics. At the curve's left minimum (Fig. 1), awe slows or pauses the subjective time. Contentment is an uncluttered, information-scarce experience that represents confidence in self-agency but lacks internal motivation.

Stress and contentment lie at opposite ends of an information-processing and action-motivation spectrum. It is a contradiction; those with the capacity to institute change (contentment) lack the desire, and

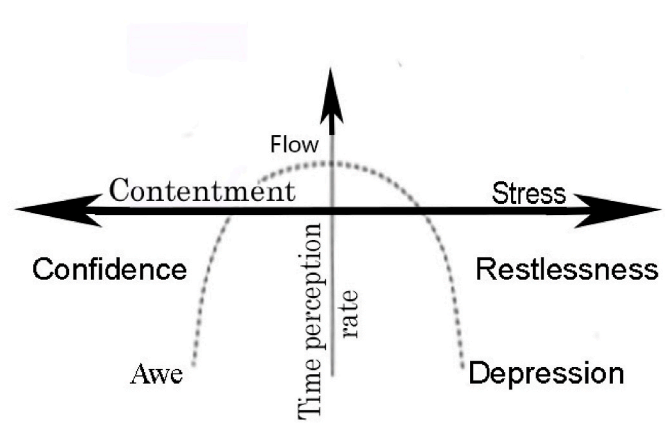

Fig. 1. The Psychology of Contentment and Stress Movement speeds up time perception (vertical arrow). In positive experiences, time perception reduces action motivation, culminating in awe. The pain of stress motivates action but weakens self-confidence. Anxiety can progress to depression when action motivation halts. A unique point of action, motivation, and confidence is flow.

Table 1
Binary choices supporting bodily and psychological equilibrium.

	Experience	
Symptom	**Positive arousal**	**Stress**
Time perception increases (Dilation) —Arousal	Parasympathetic	Action motivation
Time perception decreases (Compression)— Action	Flow	Sympathetic
Physiological symptoms (shivering, sweating)	Accomplishment	Shame, fear

those having the desire (stress) lack the agency. Gordon et al. (2023) confirmed the connection between decision-making and bodily functions and movement control: better body control (resulting in less stress) permits greater agency, and vice versa. In the following, we investigate the regulatory framework of motivation in more detail.

1.5. *The binary regulation of higher cognitive functions*

The timing of the giant fiber descending neuron spike determines whether a Drosophila evades a predator via a short or long takeoff (Ache et al., 2019). Bifurcations from geometric principles can elucidate behavior and decision-making across various species and ecological scenarios (Sridhar et al., 2021), and temperature and emotion regulation in mammals (Hesp et al., 2021; Kao et al., 2015; Sadowski et al., 2020). These spontaneous and abrupt "critical" transitions are linked with specific geometrical relationships. A shift from averaging vectorial information among options abruptly excludes one among the remaining choices. The brain repeatedly breaks down multi-choice decisions into a sequence of binary decisions. Binary regulation is an "on-off regulation," in systems with only two possible states, referring to "dichotomous thinking in psychology.

In mammals, stimulation of the PAG can induce relaxation or escape behavior. Frontal PAG stimulation inspires a relaxed, immobile posture due to the sense of excess time. However, lateral PAG stimulation also produces two typical behavioral responses. When there is sufficient time, increased blood pressure and heightened pain sensitivity facilitate escape and defensive responses (Zelena et al., 2018). An immediate threat, when escape is no longer possible, mutes pain sensitivity and triggers immobile freezing behavior. In people, anxiety can induce aggravation or an emotional collapse into depression, where both time perception and action motivation appear to halt (Stanghellini et al., 2016), providing further support for our thermodynamic argument.

Binary choices can generate multifaceted behavior regulation (summarized in Table 1), such as (1) dilation of time perception to accelerate or mute motivation, (2) contraction of time perception to mediate action toward completion, and (3) halting of action motivation or sudden cognitive changes. This regulation is based on psychological spin, utilizing the reversible perception cycle (Déli, 2023), which automatically restores psychological equilibrium, thereby forming a new balance. This model can explain regulatory complexity as a series of binary choices ad infinitum. Dopaminergic mechanisms, which can amplify the motivational power of emotions through subjective time perception, highlight how internal and external factors influence the multifaceted nature of experiences (Soares et al., 2016).

We must note that emotional and cognitive processes can trigger physiological symptoms, such as shivering, chills, sweating, and changes in body temperature (Schoeller & Perlovsky, 2016). In this context, physiological symptoms can be both tools and consequences of the brain's energy regulation.

2. Discussion

Decision-making from fruit flies to humans often boils down to binary choices based on geometric principles and critical transitions. The brain's cognitive cycle can maintain a bodily and psychological equilibrium through simple bifurcation stemming from geometric principles. Binary options can refine cognitive and intellectual evolution through learning, beliefs, and individual capabilities. Moreover, emotion, temperature, and physiological symptom regulation recover and maintain constant resting entropy. Therefore, as the thermodynamic cycle stabilizes the psyche around a new equilibrium after every decision-making, it increases or decreases synaptic complexity, confidence, and mental health.

Time perception can lead to contrasting behavioral outcomes during stress (information overload) or contentment (information scarcity). Negative emotions inspire arbitrary and chaotic performance, corresponding to wasteful energy use, which can accumulate and lead to adverse health effects associated with stress. In positive conditions, frugality of action motivation reflects a minimal energy path, allowing contentment and creativity. In contrast, faster time perception can manage ongoing action by inspiring cognitive coherence. Intrinsically motivating activities lead to deep engagement and enjoyment, a state known as flow, characterized by the intersection of motivational challenge, confidence, and passion (Csikszentmihalyi, 1990, 1997, p. 31). This is congruent to our hypothesis that ongoing action accelerates time perception. The time perception curve also overlaps Yerkes-Dodson law, providing further support to our thermodynamic foundation of emotions' potential for motivation. Emotions can be viewed as the fundamental forces of motivation.

By conceptualizing psychological processes through energy dynamics, we outlined how emotions can affect motivation through distorted time perception. Moreover, our thermodynamic model can explain how action motivation during stress can produce wasteful cognitive processes. The relationship between low entropy and compromised consciousness states (Varley et al., 2020), and depression (Wise et al., 2017) underlines the role of stress in mental problems.

Our model provides a framework for designing interventions and strategies that leverage the interconnections between emotions, motivation, and physiology. While our thermodynamic model focuses on the fundamental structural motivations underlying behavior, we acknowledge the importance of cultural norms, social expectations, and environmental factors in shaping emotional and motivational experiences.

Integrating these contextual factors is crucial to understanding the complex interplay between emotions, motivation, physiology, and subjective experiences across diverse cultural and environmental settings.

2.1. Limitations and future directions

We would like to acknowledge the lack of empirical validation and experimental testing of the proposed framework. Additionally, the generalizability of the model across diverse populations remains unexplored. This limitation is particularly salient in clinical populations, such as individuals with post-traumatic stress disorder (PTSD) or major depressive disorder, where disruptions in bodily awareness and emotional regulation may offer critical tests of the model's assumptions.

Our framework also does not yet account for the role of time perception for proprioceptive awareness—two domains that are increasingly recognized as central to embodied cognition and affective experience. Future empirical works in this area can further our understanding of the mind-body interaction.

While our thermodynamic model provides a novel framework for integrating emotions, motivation, and time perception, it remains theoretical and is subject to several significant limitations. Foremost, the model relies heavily on analogies between thermodynamic principles—such as entropy, temperature, and energy—and psychological processes. While conceptually illuminating, these analogies are not always supported by direct empirical evidence, which may limit their explanatory power. The complexity of human emotional and cognitive systems likely exceeds the reach of simplified energetic metaphors, especially when such models are extended to subjective constructs like time perception.

Additionally, many of the neurophysiological correlates we invoke, such as neural entropy or the functional role of dopamine in timing, are still under active investigation, and consensus regarding their interpretation is far from established. The use of entropy as a measure of cognitive or emotional flexibility, for example, depends on methodological choices that may not yet be standardized across studies. Furthermore, the model currently lacks specificity in distinguishing between clinical and non-clinical populations, and its generalizability across age groups, cultural settings, or neurodiverse profiles remains untested. Despite these constraints, the integrative potential of the framework may help bridge conceptual gaps between disparate findings in psychology, physiology, and neuroscience.

Nevertheless, our model opens several promising avenues for applied research and translational work. In mental health, for instance, subjective distortions of time perception are commonly reported in anxiety, depression, and trauma-related disorders. Our framework suggests that such distortions may reflect dysregulated entropy states in the brain, which could be targeted through interventions aimed at modulating physiological arousal and attentional engagement. Biofeedback, neurofeedback, or pharmacological interventions that stabilize neural entropy dynamics may be tested for their capacity to restore adaptive time perception and emotional regulation. Moreover, in performance contexts—such as athletic training, musical improvisation, or surgical decision-making—the model's emphasis on flow as a state of optimal energy alignment suggests practical strategies for cultivating cognitive and emotional balance. Future research should prioritize experimental designs that manipulate entropy-relevant parameters (e.g., arousal, cognitive load, ambient temperature) while recording physiological or neuroimaging data. Valuable direction would be to examine whether interventions known to improve well-being, such as mindfulness or physical activity, influence subjective time perception through measurable changes in brain signal complexity.

While our model identifies correlations between emotional states and physiological indices—such as body temperature and thermodynamic entropy—our current analysis stops short of demonstrating direct causal mechanisms. Establishing such causality will be the subject of future work, potentially using targeted experimental designs and interventions that modulate physiological parameters to observe downstream effects on affective and cognitive processes.

3. Conclusion

The thermodynamic analysis of cognition points to the existence of binary regulation. First observed in fruit flies and fish, this regulation can maintain bodily and psychological equilibrium and enable abstract decision-making by infinitely enhancing the details of regulatory complexity. A decision-making process based on geometric principles may be universal throughout biology and even physics, such as electromagnetism.

Our verifiable framework shows that identical dilation of time perception in arousing emotional states (such as anxiety and joy) and calming experiences (like awe and natural environments) can give rise to varied motivation and offer nuanced decision-making. Time perception, a function of information processing and entropic factors, potentiates the ability for motivation. The muting of action motivation in positive states represents energy frugality, or a minimum energy path, which might be analogous to the principle of stationary action in physics. In contrast, stress represents information overload, spurring chaotic decision-making and action motivation, which wastes effort and energy. Our model suggests that emotions have a thermodynamic foundation, rendering them the driving forces of motivation.

The implications of our model extend beyond theoretical understanding, offering potential avenues for addressing mental health challenges and optimizing well-being through interventions that leverage the interconnections between emotions, motivation, and physiology. Our thermodynamic perspective originates emotions and their long-term mental consequences in the energy-information dynamics of the brain. It opens new avenues for interdisciplinary and innovative approaches to understanding and optimizing human functioning. Finally, it can inspire novel approaches in artificial intelligence research.

CRediT authorship contribution statement

Eva Déli: Writing – review & editing, Writing – original draft, Visualization, Data curation, Conceptualization. **Felix Schoeller:** Writing – review & editing, Writing – original draft, Investigation. **Adam Safron:** Writing – review & editing, Writing – original draft. **Abhinandan Jain:** Writing – review & editing, Writing – original draft. **Arturo Tozzi:** Writing – review & editing, Writing – original draft. **Vladimir Adrien:** Writing – review & editing, Writing – original draft. **Nicco Reggente:** Writing – review & editing, Writing – original draft, Visualization, Project administration.

Data availability

No data was used for the research described in the article.

References

Ache, J. M., Polsky, J., Alghailani, S., Parekh, R., Breads, P., Peek, M. Y., Bock, D. D., Reyn, C. R., & Card, G. M. (2019). Neural basis for looming size and velocity encoding in the drosophila giant Fiber escape pathway. *Current Biology, 29*, 1073–1081.e4.

Ahissar, E., & Assa, E. (2016). Perception as a closed-loop convergence process. *eLife, 5*, Article e12830. https://doi.org/10.7554/eLife.12830

Allingham, E., Hammerschmidt, D., & Wöllner, C. (2021). Time perception in human movement: Effects of speed and agency on duration estimation. *Quarterly Journal of Experimental Psychology A, 74*(3), 559–572.

An, S. J., & Kim, D. (2011). Alterations in serotonin receptors and transporter immunoreactivities in the hippocampus in the rat unilateral hypoxic-induced epilepsy model. *Cellular and Molecular Neurobiology, 31*(8), 1245–1255. https://doi.org/10.1007/s10571-011-9726-x

Bannister, S., & Eerola, T. (2021). Vigilance and social chills with music: Evidence for two types of musical chills. *Psychology of Aesthetics, Creativity, and the Arts, 17*(2), 242–258. https://doi.org/10.1037/aca0000421.

Barrett, L. F. (2017). *Social Cognitive and Affective Neuroscience, 12*(1), 1–23.

Beerendonk, L., Mejías, J. F., Nuiten, S. A., de Gee, J. W., Fahrenfort, J. J., & van Gaal, S. (2024). A disinhibitory circuit mechanism explains a general principle of peak 726 performance during mid-level arousal. *Proceedings of the National Academy of Sciences of the United States of America, 121*, Article e2312898121, 725.

Biderman, N., Bakkour, A., & Shohamy, D. (2020). What are memories for? The hippocampus bridges past experience with future decisions. *Trends in Cognitive Sciences, 24*, 542–556.

Briese, E. (1995). Emotional hyperthermia and performance in humans. *Physiology and Behavior, 58*, 615–618.

Briese, E., & Cabanac, M. (1991). Stress hyperthermia: Physiological arguments that it is a fever. *Physlogical Behaviour, 49*, 1153–1157.

Brown, R., & Thorsteinsson, E. (2020). Arousal states, symptoms, behaviour, sleep and body temperature. In R. Brown, & E. Thorsteinsson (Eds.), *Comorbidity*. Cham: Palgrave Macmillan. https://doi.org/10.1007/978-3-030-32545-9_7.

Cabanac, M. (1999). Emotion and phylogeny. *Journal of Consciousness Studies, 6*(6–7), 176–190.

Clavijo-Baque, S., & Bozinovic, F. (2012). Testing the fitness consequences of the thermoregulatory and parental care models for the origin of endothermy. *PLoS, ONE, 7*.

Comtesse, H., Powell, S., Soldo, A., Hagl, M., & Rosner, R. (2019). Long-term psychological distress of Bosnian war survivors: An 11-year follow-up of former displaced persons, returnees, and stayers. *BMC Psychiatry, 19*.

Corcoran, J., & Zahnow, R. (2022). Weather and crime: A systematic review of the empirical literature. *Crime Sci, 11*, 16. https://doi.org/10.1186/s40163-022-00179-8

Csikszentmihalyi, M. (1990). *Flow: The psychology of optimal experience*. New York: Harper & Row.

Csikszentmihalyi, M. (1997). *Finding flow: The psychology of engagement with everyday life* (1st ed., p. 31). New York: Basic Books, 978-0-465-02411-7.

Cui, X., Yin, T., et al. (2023). The role of valence, arousal, stimulus type, and temporal paradigm in the effect of emotion on time perception: A meta-analysis. *Psychonomic Bulletin & Review, 30*, 1–21.

D'Agostino, O., Castellotti, S., & Del Viva, M. M. (2023). Time estimation during motor activity. *Frontiers in Human Neuroscience, 17*, Article 1134027. Apr 21.

Davydenko, M., & Peetz, J. (2017). Time grows on trees: The effect of nature settings on time perception. *Journal of Environmental Psychology, 54*, 20–26.

de Lara, A. C. (2020). Interpreting the high energy consumption of the brain at rest. *Proceedings, 46*(1), 30. https://doi.org/10.3390/ecea-5-06694

Déli, E. (2024). *Emotional reasoning; insight into the conscious experience*. CRC Publishing.

Déli, E. K. (2023). What is psychological spin? A thermodynamic framework for emotions and social behavior. *Psych, 5*(4), 1224–1240.

Déli, E., & Kisvarday, Z. (2020). The thermodynamic brain and the evolution of intellect: The role of mental energy. *Cognitive Neurodynamics*. https://doi.org/10.1007/s11571-020-09637-y

Déli, E., Peters, J., & Kisvarday, Z. (2021). The thermodynamics of cognition: A mathematical treatment. *Computational and Structural Biotechnology Journal, 19*, 784–793.

Déli, É., Peters, J. F., & Kisvárday, Z. F. (2022). How the brain becomes the mind: Can thermodynamics explain the emergence and nature of emotions? *Entropy, 24*.

Déli, E., Peters, J., & Tozzi, A. (2017). Relationships between short and fast brain timescales. *Cognitive Neurodynamics, 11*, 539.

Déli, E., Peters, J., & Tozzi, A. (2018). The thermodynamic analysis of neural computation. *J Neurosci Clin Res., 3*, 1.

Dempsey, W. P., Du, Z., Nadtochiy, A., et al. (2022). Regional synapse gain and loss accompany memory formation in larval zebrafish. *PNAS, 119*(3), Article e2107661119.

Di Lernia, D., Serino, S., Pezzulo, G., Pedroli, E., Cipresso, P., & Riva, G. (2018). Feel the time. Time perception as a function of interoceptive processing. *Frontiers in Human Neuroscience, 12*.

Droit-Volet, S., Dambrun, M., & Monier, F. (2024). Awe and time perception. *Acta Psychologica, 245*, Article 104232. https://doi.org/10.1016/j.actpsy.2024.104232

Droit-Volet, S., & Fayolle, S. (2024). The conscious awareness of time distortions regulates the effect of emotion on the perception of time. *Acta Psychologica, 245*, Article 104232.

Escobar, F. B., Velasco, C., Motoki, K., & Wang, Q. J. (2020). The temperature of emotions. *PLoS One, 16*.

Failing, M., & Theeuwes, J. (2016). Reward alters the perception of time. *Cognition, 148*, 19–26.

Farmer, C. G. (2020). Parental care, destabilizing selection, and the evolution of tetrapod endothermy. *Physiology, 35*(3), 160–176.

Fazekas, C. L., Bellardie, M., Török, B., et al. (2021). Pharmacogenetic excitation of the median raphe region affects social and depressive-like behavior and core body temperature in Male mice. *Life Sciences*, Article 120037.

Fossat, P., Bacqué-Cazenave, J., Deurwaerdère, P. D., Cattaert, D., & Delbecque, J. (2015). Serotonin, but not dopamine, controls stress response and anxiety-like behavior in crayfish, Procambarus clarkii. *Journal of Experimental Biology*. https://doi.org/10.1242/jeb.120550

Fredericks, C. A., Sturm, V. E., Brown, J. A., Hua, A. Y., Bilgel, M., Wong, D. F., … Seeley, W. W. (2018). Early affective changes and increased connectivity in preclinical Alzheimer's disease. *Alzheimer's & Dementia : Diagnosis, Assessment & Disease Monitoring, 10*, 471–479.

Frosini, M., Sesti, C., Palmi, M., Valoti, M., Fusi, F., Mantovani, P., Bianchi, L., Della, C. L., & Sgaragli, G. (2000). The possible role of taurine and GABA as endogenous cryogens in the rabbit: Changes in CSF levels in heat-stress. *Advances in Experimental Medicine and Biology, 483*, 335–344.

Gable, P. A., & Poole, B. D. (2012). Perception time flies when you're having approach-motivated fun. *Effects of Motivational Intensity on Time, 23*(8). https://doi.org/10.1177/0956797611435817

Gable, P. A., Wilhelm, A. L., & Poole, B. D. (2022). How does emotion influence time perception? A review of evidence linking emotional motivation and time processing. *Frontiers in Psychology, 13*.

Gibbon, J., Church, R. M., & Meck, W. H. (1984). Scalar timing in memory. *Annals of the New York Academy of Sciences, 423*(1), 52–77.

Gibbon, J., Church, R. M., & Meck, W. H. (1984). Scalar timing in memory. *Annals of the New York Academy of Sciences, 423*(1), 52–77.

Gladhill, K. A., Mioni, G., & Wiener, M. (2022). Dissociable effects of emotional stimuli on electrophysiological indices of time and decision-making. *PLoS One, 17*.

Gordon, E. M., Chauvin, R. J., Van, A. N., et al. (2023). A somato-cognitive action network alternates with effector regions in motor cortex. *Nature, 617*, 351–359.

Green, B., Kavanagh, D., & Young, R. (2003). Being stoned: A review of self-reported cannabis effects. *Drug and Alcohol Review, 22*(4), 453–460.

Grigg, G., Nowack, J., Bicudo, J., Bal, N. C., Woodward, H. N., & Seymour, R. S. (2021). Whole-body endothermy: Ancient, homologous and widespread among the ancestors of mammals, birds and crocodylians. *Biological Reviews, 97*.

Groenink, L., Compaan, J., van der Gugten, J., Zethof, T., van der, H. J., & Olivier, B. (1995). Stress-induced hyperthermia in mice pharmacological and endocrinological aspects. *Annals of the New York Academy of Sciences, 771*, 252–256.

Hall, M., Vasko, R., Buysse, D., Ombao, H., Chen, Q., et al. (2004). Acute stress affects heart rate variability during sleep. *Psychosomatic Medicine, 66*, 56–62.

Hallez, Q., Paucsik, M., Tachon, G., Shankland, R., Marteau-Chasserieau, F., & Plard, M. (2023). How physical activity and passion color the passage of time: A response with ultra-trail runners. *Frontiers in Psychology, 13*.

Hesp, C., Smith, R., Parr, T., Allen, M., Friston, K., & Ramstead, M. J. (2021). Deeply felt affect: The emergence of valence in deep active inference. *Neural Computation, 33*, 1–49.

Hoagland, H. (1933). The physiological control of judgments of duration: Evidence for a chemical clock. *The Journal of General Psychology, 9*, 267–287.

Hollis, F., van der Kooij, M. A., Zanoletti, O., Lozano, L., Cantó, C., & Sandi, C. (2015). Mitochondrial function in the brain links anxiety with social subordination. *Proceedings of the National Academy of Sciences, 112*, 15486–15491.

Hosseini Houripasand, M., Sabaghypour, S., Farkhondeh Tale Navi, F., & Nazari, M. A. (2023). Time distortions induced by high-arousing emotional compared to low-arousing neutral faces: An event-related potential study. *Psychological Research*, 1–12.

Huang, Z., Zhang, J., Wu, J., Mashour, G. A., & Hudetz, A. G. (2020). Temporal circuit of macroscale dynamic brain activity supports human consciousness. *Science Advances, 6*, Article eaaz0087.

Inagaki, T. K., Hazlett, L. I., & Andreescu, C. (2019). Naltrexone alters responses to social and physical warmth: Implications for social bonding. *Social Cognitive and Affective Neuroscience, 14*, 471–479.

Ince, R. A., Giordano, B. L., Kayser, C., Rousselet, G. A., Gross, J., & Schyns, P. G. (2017). A statistical framework for neuroimaging data analysis based on mutual information estimated via a gaussian copula. *Human Brain Mapping, 38*(3), 1541–1573.

Jizba, P., & Arimitsu, T. (2001). *The world according to Renyi: thermodynamics of fractal systems, 597* pp. 341–348). AIP Conference Proceedings.

Kao, F.-C., Wang, S. R., & Chang, Y. (2015). Brainwaves analysis of positive and negative emotions. *ISAA*, (12), 1263–1266.

Kataoka, N., Shima, Y., Nakajima, K., & Nakamura, K. (2020). A central master driver of psychosocial stress responses in the rat. *Science, 367*, 1105–1112.

Keller, A. S., Leikauf, J. E., Holt-Gosselin, B., Staveland, B. R., & Williams, L. (2019). Paying attention to attention in depression. *Translational Psychiatry, 9*.

Kent, L. (2023). Mental gravity: Depression as spacetime curvature of the self, mind, and brain. *Entropy, 25*(9), 1275.

Kluger, M. J., O'Reilly, B. J., Shope, T. R., & Vander, A. J. (1987). Further evidence that stress hyperthermia is a fever. *Physiology & Behavior, 39*(6), 763–766. https://doi.org/10.1016/0031-9384(87)90263-0

Kowal, M. A., Hazekamp, A., Colzato, L. S., et al. (2015). Cannabis and creativity: Highly potent cannabis impairs divergent thinking in regular cannabis users. *Psychopharmacology (Berl)., 232*(6), 1123–1134.

Larson, E. A. (2004). The time of our lives: The experience of temporality in occupation. *Can J Occup Ther. Feb, 71*(1), 24–35.

Lehockey, K. A., Winters, A. R., Nicoletta, A. J., et al. (2018). The effects of emotional states and traits on time perception. *Brain Inf, 5*, 9.

The brain as a closed system modulated by the senses. In Llinás, R., & Paré, D. and M. (Eds.), *The churchlands and their critics*, (1996). Cambridge, Mass: Blackwell Publishers.

Lowry, C. A., Lightman, S. L., & Nutt, D. J. (2009). That warm fuzzy feeling: Brain serotonergic neurons and the regulation of emotion. *Journal of Psychopharmacology, 23*, 392–400.

Lupien, S. J., Maheu, F. S., Mt, T., Fiocco, A. J., & Schramek, T. E. (2007). The effects of stress and stress hormones on human cognition: Implications for the field of brain and cognition. *Brain and Cognition, 65*, 209–237.

Ma, A. C., Cameron, A. D., & Wiener, M. (2024). Memorability shapes perceived time (and vice versa). *Nature Human Behaviour*. https://doi.org/10.1038/s41562-024-01863-2

Madden, C. J., & Morrison, S. F. (2019). Central nervous system circuits that control body temperature. *Neuroscience Letters, 696*, 225–232.

Martinelli, N., & Droit-Volet, S. (2022). Judgment of duration and passage of time in prospective and retrospective conditions and its predictors for short and long durations. *Scientific Reports, 12*, Article 22241.

Mason, A. E., Kasl, P., Soltani, S., et al. (2024). Elevated body temperature is associated with depressive symptoms: Results from the TemPredict study. *Scientific Reports, 14*, 1884. https://doi.org/10.1038/s41598-024-51567-w
Meeusen, R., Van Cutsem, J., & Roelands, B. (2020). Endurance exercise-induced and mental fatigue and the brain. *Experimental Psychology, 106*, 2294–2298.
Mitchell, J. M., Weinstein, D., Vega, T. A., & Kayser, A. S. (2015). Dopamine, time perception, and future time perspective. *Psychopharmacology, 235*, 2783–2793.
Moe, R. O., & Bakken, M. (1997). Effects of handling and physical restraint on rectal temperature, cortisol, glucose and leucocyte counts in the silver fox (vulpes vulpes). *Acta Veterinaria Scandinavica, 38*, 29–39.
Morimoto, A., Watanabe, T., Morimoto, K., Nakamori, T., & Murakami, N. (1991). Possible involvement of prostaglandins in psychological stress-induced responses in rats. *The Journal of Physiology, 443*(1), 421–429.
Nashiro, K., Min, J., Yoo, H. J., et al. (2022). Increasing coordination and responsivity of emotion-related brain regions with a heart rate variability biofeedback randomized trial. *Cognitive, Affective, & Behavioral Neuroscience, 23*, 66–83.
Nestler, E. J., & Russo, S. J. (2024). Neurobiological basis of stress resilience. *Neuron, 112*, 1911–1929.
Northoff, G. (2018). Is our brain an open or closed system? Prediction model of brain and world–brain relation. In *The spontaneous brain*. MIT press.
Northoff, G., & Tumati, S. (2019). "Average is good, extremes are bad" – non-Linear inverted U-shaped relationship between neural mechanisms and functionality of mental features. *Neuroscience & Biobehavioral Reviews, 104*, 11–25.
Nowack, J., Giroud, S., Arnold, W., & Ruf, T. (2017). Muscle non-shivering thermogenesis and its role in the evolution of endothermy. *Frontiers in Physiology, 8*.
Nutt, D. J. (1999). Care of depressed patients with anxiety symptoms. *Journal of Clinical Psychiatry, 60*(Suppl 17), 23–27. ; discussion 46-8.
O'Connor, D. B., Thayer, J. F., & Vedhara, K. (2020). Stress and health: A review of psychobiological processes. *Annual Review of Psychology*.
Ogden, R., Alatrany, S. S. J., Flaiyah, A. M., Ali, S., Aldrraji, H., Musa, H., Alatrany, A. S. S., et al. (2024). Distortions to the passage of time for annual events: Exploring why christmas and ramadan feel like they come around more quickly each year. *PLoS One, 19*(7), Article e0304660.
Ogden, R. S., Henderson, J., McGlone, F., & Richter, M. (2019). Time distortion under threat: Sympathetic arousal predicts time distortion only in the context of negative, highly arousing stimuli. *PLoS One, 14*(5), Article e0216704.
Oka, T., Oka, K., & Hori, T. (2001). Mechanisms and mediators of psychological stress-induced rise in core temperature. *Psychosomatic Medicine, 63*(3), 476–486. https://doi.org/10.1097/00006842-200105000-00018
Paasche, C., Weibel, S., Wittmann, M., & Lalanne, L. (2019). Time perception and impulsivity: A proposed relationship in addictive disorders. *Neuroscience & Biobehavioral Reviews, 106*, 182–201. Nov.
Parrott, R. F., Vellucci, S. V., Forsling, M. L., & Goode, J. A. (1995). Hyperthermic and endocrine effects of intravenous prostaglandin administration in the pig. *Domestic Animal Endocrinology, 12*, 197–205.
Quadt, L., Critchley, H. D., & Nagai, Y. (2022). Cognition, emotion, and the central autonomic network. *Autonomic Neuroscience, 238*.
Raichle, M. E. (2010). Two views of brain function. *Trends in Cognitive Sciences, 14*(4), 180–190. https://doi.org/10.1016/j.tics.2010.01.008. Epub 2010 Mar 4. PMID: 20206576.
Raison, C. L., Hale, M. W., Williams, L. E., Wager, T. D., & Lowry, C. A. (2015). Somatic influences on subjective well-being and affective disorders: The convergence of thermosensory and central serotonergic systems. *Frontiers in Psychology, 5*, 1589.
Remmers, C., & Zander, T. (2018). Why you don't see the forest for the trees when you are anxious: Anxiety impairs intuitive decision making. *Clinical Psychological Science, 6*, 48–62.
Robbe, D. (2023). Lost in time: Relocating the perception of duration outside the brain. *Neuroscience & Biobehavioral Reviews, 153*, Article 105312.
Rudd, M., Vohs, K. D., & Aaker, J. L. (2012). Awe expands people's perception of time, alters decision making, and enhances well-being. *Psychological Science, 23*, 1130–1136.
Rutrecht, H. M., Wittmann, M., Khoshnoud, S., & Igarzábal, F. A. (2021). Time speeds up during flow states: A study in virtual reality with the video game thumper. *Timing & Time Perception, 9*(4), 353–376.
Sadowski, S., Fennis, B. M., & van Ittersum, K. (2020). Losses tune differently than gains: How gains and losses shape attentional scope and influence goal pursuit. *Cognition & Emotion, 34*, 1439–1456.
Schoeller, F., & Perlovsky, L. I. (2016). Aesthetic chills: Knowledge-acquisition, meaning-making, and aesthetic emotions. *Frontiers in Psychology, 7*.
Seebacher, F. (2009). Responses to temperature variation: Integration of thermoregulation and metabolism in vertebrates. *Journal of Experimental Biology, 212*, 2885–2891.
Seebacher, F. (2020). Is endothermy an evolutionary by-product? *Trends in Ecology & Evolution, 35*(6), 503–511.
Şen, B., Kurtaran, N. E., & Öztürk, L. (2023). The effect of 24-hour sleep deprivation on subjective time perception. *International Journal of Psychophysiology, 192*, 91–97. https://doi.org/10.1016/j.ijpsycho.2023.08.011
Simen, P., & Matell, M. (2016). Why does time seem to fly when we're having fun? *Science, 354*(6317), 1231–1232.
Singer, W. (2021). Recurrent dynamics in the cerebral cortex: Integration of sensory evidence with stored knowledge. *PNAS, 118*.
Soares, S., Atallah, B. V., & Paton, J. J. (2016). Midbrain dopamine neurons control judgment of time. *Science, 354*, 1273–1277.
Spapé, M. M., Harjunen, V. J., & Ravaja, N. (2021). Time to imagine moving: Simulated motor activity affects time perception. *Psychonomic Bulletin & Review, 29*, 819–827.
Sridhar, V. H., Li, L., Gorbonos, D., Nagy, M., Schell, B. R., Sorochkin, T., Gov, N. S., & Couzin, I. D. (2021). The geometry of decision-making in individuals and collectives. In *Proceedings of the national academy of sciences of the United States of America* (Vol. 118).
Stanghellini, G., Ballerini, M., Presenza, S., Mancini, M., Northoff, G., & Cutting, J. (2016). Abnormal time experiences in major depression. An empirical qualitative study. *Psychopathology*. https://doi.org/10.1159/000452892
Terlouw, E. M., Kent, S., Cremona, S., & Dantzer, R. (1996). Effect of intracerebroventricular administration of vasopressin on stress-induced hyperthermia in rats. *Physiology and Behavior, 60*, 417–424.
Thönes, S., & Oberfeld, D. (2015). Time perception in depression: A meta-analysis. *Journal of Affective Disorders, 175*, 359–372.
Toso, A., Fassihi, A., Paz, L., Pulecchi, F., & Diamond, M. E. (2020). A sensory integration account for time perception. *PLoS Computational Biology, 17*.
van der Heyden, J. A., Zethof, T. J., & Olivier, B. (1997). Stress-induced hyperthermia in singly housed mice. *Physiology and Behavior, 62*, 463–470.
van Hedger, K., Necka, E. A., Barakzai, A. K., & Norman, G. J. (2017). The influence of social stress on time perception and psychophysiological reactivity. *Psychophysiology, 54*(5), 706–712. https://doi.org/10.1111/psyp.12836
Varley, T. F., Carhart-Harris, R., Roseman, L., Menon, D. K., & Stamatakis, E. A. (2020). Serotonergic psychedelics LSD & psilocybin increase the fractal dimension of cortical brain activity in spatial and temporal domains. *NeuroImage, 220*(October), Article 117049.
Wackermann, J., & Ehm, W. (2006). The dual klepsydra model of internal time representation and time reproduction. *Journal of Theoretical Biology, 239*(4), 482–493.
Wang, D. J., Jann, K., Fan, C., et al. (2018). Neurophysiological basis of multiscale entropy of brain complexity and its relationship with functional connectivity. *Frontiers in Neuroscience, 12*, 352.
Francois. (1927). In J. H. Wearden (Ed.), *Timing & time perception: Vol. 2019. Body temperature and the sense of time. Translated*.
Wearden, J. H., & Penton-Voak, I. S. (1995). Feeling the heat: Body temperature and the rate of subjective time, revisited. *Quarterly Journal of Experimental Psychology B Comparative and Physiological Psychology, 48B*(2), 129–141.
Williams, L. E., & Bargh, J. A. (2008). Experiencing physical warmth promotes interpersonal warmth. *Science, 322*(5901), 606.
Wise, T., Marwood, L., Perkins, A. M., et al. (2017). Nstability of default mode network connectivity in major depression: A two-sample confirmation study. *Translational Psychiatry, 25*(7), Article e1105, 4.
Wittmann, M. (2009). The inner experience of time: Neural mechanisms and psychological processes. *Philosophical Transactions of the Royal Society B, 364*(1525), 1955–1967.
Wittmann, M. (2015). Modulations of the experience of self and time. *Consciousness and Cognition, 38*, 172–181.
Wittmann, M., & Paulus, M. P. (2008). Decision making, impulsivity and time perception. *Trends Cogn Sci. Jan, 12*(1), 7–12.
Yang, S., Zhao, Z., & Cui, H. (2019). Temporal variability of cortical gyral-sulcal resting state functional activity correlates with fluid intelligence. *Frontiers in Neural Circuits, 13*, 36.
Yerkes, R. M., & Dodson, J. D. (1908). The relation of strength of stimulus to rapidity of habit-formation. *Journal of Comparative Neurology and Psychology, 18*(5), 459–482. Lupien SJ).
Zanin, M., Güntekin, B., Aktürk, T., Hanoğlu, L., & Papo, D. (2019). Time irreversibility of resting-state activity in the healthy brain and pathology. *Frontiers in Physiology, 10*.
Zelena, D., Menant, O., Andersson, F., & Chaillou, E. (2018). Periaqueductal gray and emotions: The complexity of the problem and the light at the end of the tunnel, the magnetic resonance imaging. *Endocrine Regulations, 52*, 222–238.
Zmigrod, L., Zmigrod, S., Rentfrow, P. J., & Robbins, T. (2019). The psychological roots of intellectual humility: The role of intelligence and cognitive flexibility. *Personality and Individual Differences, 141*, 200–208.
Wang, J., & Lapate, R. C. (2024). Emotional state dynamics impacts temporal memory. *Cognition and Emotion, 39*, 136–155.
Shannon, C. E. (1993). Collected Papers. In Claude E. Shannon (Ed.)*, vol. 7. Coding Theorems for a Discrete Source With a Fidelity Criterion Institute of Radio Engineers, International Convention Record* (pp. 325–350). IEEE.
Baez, J. C. (2011). Entropy and Free Energy. *arXiv:1102.2098 [quant-ph]*.