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THE EQUATIONS FOR CONSCIOUSNESS: A REPLY TO "TRACKING THE TRAVELS," A REVIEW OF *JOURNEY OF THE MIND*

A complete theory of consciousness should explain:

How physical activity in biological structures generates *conscious experience* (awareness)

How activity generates *first-person experience* (self-awareness: "I am experiencing an experience")

The *biological functions* of consciousness (the purpose of experience)

Which *brain structures* can (and cannot) produce experience

Which forms of *neural activity* can (and cannot) produce experience

Which types of *mental representations* can (and cannot) enter consciousness

Which forms of *learning* can (and cannot) produce experience

Which *brain waves* are biomarkers of consciousness

The *temporal profile* of consciousness (how an experience physically evolves over time)

Only one theory offers precise, falsifiable explanations of all nine questions within a unified mathematical framework, a framework we will refer to as unified resonance theory (URT). URT is an integrated set of mechanistic models of most forms of human cognition, both conscious and unconscious, including:

Visual perception and recognition

Auditory perception and recognition

Locating a target in a complex visual or acoustic scene

Reaching for a target

Spatial navigation

Volition

Motor control

Perceptual and cognitive learning

Reinforcement learning

Sequential learning (including learning melodies, toolmaking, and language)

Valuation and value-based decision making (i.e., emotions)

Understanding symbolic meaning

These models feature nonlinear, nonlocal, nonstationary mathematics developed incrementally over the past 65 years, primarily by Stephen Grossberg. URT is comprehensively described in Grossberg's 2021 monograph *Conscious Mind, Resonant Brain* (CMRB), the reference for all assertions in this reply unless otherwise specified.

URT is complex. CMRB is more than 500,000 words, most of it highly technical and conceptually challenging. (By comparison, *Quantum Field Theory and the Standard Model*, a comprehensive account of quantum physics published in 2014, stretches to 330,000 words.) URT is interdisciplinary, uniting behavioral, anatomical, physiological, biophysical, biochemical, psychological, and clinical data. The mathematics in URT consists largely of dynamic systems unique to mental activity. For researchers without suitable mathematical training, URT can be daunting. For laypeople, URT is downright inscrutable. That's why we wrote *Journey of the Mind:* to present accessible versions of URT's key ideas to a popular audience. The challenge, as we saw it, was akin to explaining relativity and quantum physics to nonscience readers. We didn't write *Principia Mathematica*. We wrote *Astrophysics for People in a Hurry*.

Likewise, it would be impossible to adequately summarize URT for an academic audience within this limited reply, so instead we'll highlight URT's defining concepts and share its explanations of the nine questions posed above.

URT is a theory of biological cognition, particularly human cognition. Consciousness is but one form of cognition modeled by URT. Perhaps its most important claim is that biological cognition—including consciousness—does not consist of a special form of matter, energy, force, or biological material. Cognition (including consciousness) is an activity. The fallacy of conflating things with activities has troubled scientists for centuries. Physicists once believed heat was a fluid they dubbed caloric. Chemists once believed combustion was a substance they called phlogiston. Biologists once searched for élan vital, the special stuff presumed to endow inanimate objects with the vivacity of life. Today, scientists understand that heat, combustion, and life are all activities that can be explained with quantitative models of collective real-time dynamics.

The same misconception has long plagued the study of consciousness: assuming there must be consciousness-producing material (like quantum microtubules, conscious cells, consciousness genes, or an undiscovered property of matter) rather than consciousness-producing activity. It's been difficult for our human minds to intuit what this activity might be, just as our inborn cognitive biases lead us away from thinking of heat, fire, and life as activities.

URT models most forms of human mental activity. These models consist of mechanisms, equations, and constraining principles. URT can be distinguished from other approaches to consciousness by its model development method, the method of minimal anatomies. This method is designed to identify, generate, and heed constraints: empirical restrictions on the operation of mental activity imposed by physics or biology.

Constraints are necessary to explain why one form of mental activity (e.g., locating a target) generates conscious experience, but another activity (e.g., reaching for a target) does not. Knowledge of the physical and functional constraints that shape biological consciousness (and distinguish, for instance, the subjective experience of seeing from knowing) enables theorists to discard many conjectured mental entities as untenable, such as philosophical zombies, conscious cells, or consciousness-generating microtubules, in the same manner that knowing that information cannot travel faster than light permits theorists to reject conjectured faster-than-light communication systems as untenable.

Physics provides a vivid example of the model-refining power of constraints: After the astronomical discovery of gamma ray bursts (GRBs) in 1967, hundreds of incompatible models of potential sources of GRBs were proposed, including models of nearby white dwarfs, pulsars, and supernovae. In 1997, a physical constraint was finally discovered that allowed physicists to reject almost all the proposed models: GRBs were found to be associated with fading X-ray emissions, a constraint that enabled researchers to determine that GRBs were emitted by extremely distant galaxies (Hurley, 2003).

One example of a constraint on theories of biological consciousness is the noise–saturation dilemma, a functional constraint that arises in any network of neurons that processes distributed patterns of inputs, including patterns that generate conscious experience. Because an individual cell can produce only a small range of activity in response to an input, a weak input will tend to produce a cellular response indistinguishable from biological noise, and a strong input will tend to drive the neuron's activity to its maximum value. This means that most inputs to a neuron will not produce a distinctive response but instead produce information-erasing saturation or noise. Nevertheless, our brain has solved the noise–saturation dilemma: Humans can consciously discern a single photon in the dark (Tinsley et al., 2016) and consciously recognize objects when quintillions of photons flood the retina in sunlight. Thus, a theory of consciousness that does not incorporate an explicit solution to the noise–saturation dilemma must be considered tentative, and a theory that cannot specify, even in principle, how it might solve the noise–saturation dilemma is a dead end.

The method of minimal anatomies imposes three main forms of constraints on models of biological cognition. First, constraints are identified through large cross-disciplinary data sets, including biological, behavioral, and psychological data. First-pass models are developed that fit one dataset, then the model is tested and refined against other datasets. Next, and most crucially, the tentative model must be shown to be consistent and compatible with previously established models of cognition. All neural dynamics within a vertebrate mind are physically integrated; thus, if it's not possible to integrate, say, a proposed model of visual recognition and an established model of visual localization within a single consistent mechanistic and mathematical framework, then the proposed model contains an error and should be discarded. This "compatibility" requirement imposes a rigorous constraint on model development.

Finally, as multiple models of mental activity are developed and integrated, it becomes possible to identify generalized functional constraints that operate across varied forms of cognition, such as the noise–saturation dilemma, the stability–plasticity dilemma, and the exploration–exploitation dilemma—constraints that can be used to guide future models.

URT's reliance on the method of minimal anatomies means that URT's approach to consciousness was bottom-up rather than top-down. Most theories of consciousness (including global workspace theory and integrated information theory) attempt to tackle consciousness head-on, as a special standalone problem; this has led many researchers to refer to consciousness as "the hard problem." Instead, Grossberg developed models of varied forms of cognition (e.g., perceptual learning, emotional valuation) and attempted to unify these models within a single mathematical framework. As URT's collection of models expanded and developed, it became possible to identify the mechanisms, dynamics, and reasons that dictate which forms of mental activity embody conscious experience.

Indeed, the special neural dynamic responsible for consciousness—*resonance*—"jumped out" of these integrated models. In other words, instead of treating consciousness as a singular hard problem, URT tackled all the so-called easy problems (such as auditory perception, sequential learning, the noise–saturation dilemma) and discovered that the neural dynamic of consciousness was hiding within the "easy" problems all along.

Here's a synopsis of URT's explanations of the nine questions posed above (these explanations are expounded upon in rich detail in CMRB):

Functions

Consciousness is a biological adaptation that serves multiple functions simultaneously, including learning, attention management, and uncertainty resolution. Every conscious experience is a learning experience: Consciousness triggers match-based learning, adding a new memory or updating an existing memory. In a mind made up of numerous parallel functional dynamics attending independent stimuli (e.g., simultaneously seeing a friend, hearing a car honking, and feeling pain from a toothache) and lacking any centralized "decider," consciousness serves as the mechanism that decides which stimulus the entire mind should focus on. The dynamics of consciousness recruit other functional dynamics to attend to this priority stimulus (e.g., switching from looking at a friend to looking for the honking car). The dynamics of consciousness also perform a hierarchical resolution of uncertainty, systematically resolving the uncertainty inherent to any perceptual stimulus, determining, for instance, that a perceived orange circle is a basketball, not a sun or an orange. The functional problems of attention management and uncertainty resolution arise only in advanced (i.e., vertebrate) minds that deal with categorizable objects. Lesser minds, such as those of invertebrates and microbes, have no need for consciousness because they do not confront the same cognitive challenges.

Activity

The neural dynamic that embodies conscious experience is resonance. Resonance is the joint neural activity of a bottom-up mental representation (the observed facts) and a top-down representation (the learned expectation) within a particular functional module (such as visual recognition). Resonance amplifies, prolongs, and synchronizes the activity of the two representations (such as an incoming representation of an orange sphere and a stored representation of a basketball). Resonance triggers learning and alerts other mental modules that there is a disambiguated stimulus worthy of attention. All conscious states are resonant states; nonresonant states cannot become conscious. Why, of all forms of physical activity, is resonance the special dynamic of consciousness? Because it is the rubber-meets-the-road mechanism by which a purposeful mind adapts to an uncertain world, the moment when the mind's physical state shifts from searching and evaluating to knowing and feeling. Resonant states in different brain structures (such as the visual recognition module and auditory recognition module) can resonate together, generating multimodal conscious experience (e.g., "I simultaneously see and hear the basketball"). Grossberg explicitly identified resonant dynamics as embodying conscious experience in 1982.

Representations

Only mental representations expressing distinctive features can enter consciousness. For example, the features of a visual representation may include color, shape, and texture; a value representation's features may include aversiveness, utility, and intensity. Mental representations that do not include distinctive features (such as the targeting module's representation of the changing distance from your finger to an elevator button you want to press) cannot become conscious. The specific physical dynamics that represent a feature embody the subjectively experienced qualities of that feature.

Learning

Only match-based learning can produce conscious experience. Match-based learning compares a bottom-up perceptual or conceptual representation to a top-down memory representation. When a match between representations is detected, resonance occurs, conscious experience occurs, and the memory representation is updated with information from the bottom-up representation. Mismatch-based learning also compares two representations, but instead of attempting to match the two representations, the dynamics of mismatch learning attempt to drive the difference between the two representations to zero.

Mismatch-based learning generates neither features nor resonance, so it cannot generate consciousness. Match-based learning is used by visual and auditory recognition, visual and auditory localization, and emotional evaluation and decision making. Mismatch-based learning is used for motor control during visual and auditory targeting.

Structures

In mammals, consciousness is generated by recurrent corticocortical and corticothalamic circuits capable of match-based learning through resonant dynamics and feature-based representations. URT explains how the six-layer architecture of the mammalian cortex is specialized for match-based learning and resonant dynamics (see Grossberg's LAMINART models). Although Grossberg does not explicitly speculate about nonmammalian brains, URT's mechanisms and mathematics predict that fish, amphibians, reptiles, and birds also contain recurrent brain structures that perform match-based learning with resonant dynamics.

Brain waves

The resonant dynamics of human conscious experience generate (faster) gamma oscillations, and a mismatch between a bottom-up input and top-down memory generates (slower, nonconscious) beta oscillations.

Temporal profile

Consider the phenomenological time line as you notice a stranger, look at their face, then suddenly realize that the person is an old friend you haven't seen in years. URT predicts that each moment of this time line is associated with distinct and discernible neural dynamics, including bursts of gamma and beta oscillations that alternate over time, with the final gamma oscillations associated with the experience of recognition featuring the highest spiking rates.

Awareness

The above explanations make falsifiable predictions about the relationship between physical activity and conscious experience. For instance, if mismatch-based learning, mental representations without features, or nonresonant neural dynamics were shown to be associated with conscious experience, then URT's account of consciousness would be proven wrong. Nevertheless, understanding how activity generates awareness ultimately involves adopting a new perspective rather than making a prediction—adopting the same perspective that views combustion not as a special thing (like phlogiston) but as a special activity that can be characterized quantitatively. Crucially, this perspective views a well-defined form of collective real-time molecular activity as combustion—understanding combustion as nothing more or less than the (constrained, predictable) dynamics of matter. Similarly, Grossberg contends, "It cannot be overemphasized that these resonances are not just correlates of consciousness. Rather, they embody the subjective properties of individual conscious experiences." The historic failure of scientists to understand that heat, combustion, and life are the emergent properties of physical activity was ultimately a failure of imagination—a failure to appreciate the true complexity of the underlying physical processes that give rise to these phenomena. The dynamics of vertebrate minds are extremely complex but not unfathomably so. The math and mechanisms that make up URT—which, despite its mature state, remains an incomplete theory of biological cognition—are intellectually demanding and resist concise synopsis, requiring mathematical training on the same order as that required to develop competence in quantum mechanics. But why would we expect it to be otherwise? The mind sciences have notoriously lagged behind the physical sciences. The formidable depth of URT suggests that one reason for our discipline's comparatively sluggish performance has been the sheer nonintuitive complexity of the physical principles supporting biological cognition.

Self-awareness

Although Grossberg does not explicitly distinguish between awareness and self-awareness, we interpret URT as suggesting a clear functional and physical distinction between awareness (experienced by all vertebrate minds) and self-awareness (experienced only by certain humans in societies with sufficiently advanced concepts). The conscious experience "I am experiencing consciousness" arises out of the intermodular resonance between the resonant states in two modules: first, in one of many consciousness-generating neural modules that humans share with other vertebrates (e.g., visual recognition) and, second, in the exclusively human language module. The language dynamics themselves must be sufficiently advanced to facilitate self-awareness: The individual's own language capability must be sufficiently advanced, and the concepts encoded within society's language dynamics must be sufficiently sophisticated, encoding concepts like "soul," "self," "consciousness," and "introspection." (Consider the challenge of explaining to an infant or chimpanzee how to become aware of their own awareness.)

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REPLY TO A REPLY

Ogas and Gaddam's reply to my review of their book *Journey of the Mind* covers a lot of ground. Little of it, alas, deals with the issues I raised. It is largely an expansion of Steven Grossberg's resonance theory which, of course, played a prominent role in the book. I have no problems with Grossberg's model. It is an interesting, influential, quantitative approach to human cognitive functioning that uses neural nets to capture the operations of "modules." But it's not going to result in an understanding of the origins of minds. Also, as noted in my review, it's seriously lacking in key features such as embodiment, movement, affect, development, aging, and socialization.

It is not the complete theory of the human mind that Ogas and Gaddam appear to believe it is. For one, it does not enable theorists "to discard conjectured mental entities . . . such as . . . conscious cells." The sentient cell is a central feature of my cellular basis of consciousness theory. It is also a fundamental element in a variety of approaches to cell biology and, as argued in a variety of recent publications, a necessary feature of the first unicellular species. Without sentience the original prokaryotes would have been Darwinian dead ends. Without valenced perceptions and directed, volitional movement they could not have survived the tumultuous environment they emerged into.

But the book has "Journey" in the title, and my problem was with the nature of the trip they took us on. The early sections are, as noted, "muddled" when it comes to the functions of species that lack nervous systems. The material on cell biology is wrong in many places. The "emergentist's dilemma" is not even acknowledged. They claim that species without nervous systems cannot have an existential consciousness but provide no reason why this should be true. Did things change when neurons evolved? Of course. But things changed many times over geological time: eukaryotic species, multicellularity, photosynthesis, oxygen production, warm-blooded metabolism, legs, and so on.

I appreciate that Ogas and Gaddam "wrote *Journey of the Mind* to present accessible versions of URT's key ideas to a popular audience." But they didn't do that until the second half. And when they made this move to Grossberg's theory, the sole focus was on human cognitive functions, not the earlier evolutionary mechanisms that preceded the emergence of *Homo sapient* minds.

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RATIONALITY NOW!

Rationality: What It Is, Why It Seems Scarce, Why It Matters

By Steven Pinker. New York: Viking, 2021. 432 pp. Hardcover, $25.49.

People are crazy and times are strange.
—Dylan

Steven Pinker, being a public intellectual, may expect readers of his *Rationality: What It Is, Why It Seems Scarce, Why It Matters* (RAT) to bring certain hopes and expectations to the task. They know Pinker as a distinguished expert on linguistics, communication, and cognitive science, a scholar with a deep knowledge of many theories from evolution to cognitive dissonance, a child of the Enlightenment and a prophet of progress. They will not be disappointed.

Readers with sensitivity and memory may recall that Pinker sometimes oversells his message. *How the Mind Works* (Pinker, 1997), for example, was a wild and fun ride through the cognitive science of