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Introduction to the special issue on physics of mind

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Abstract

In recent years, both fields of physics and psychology have made important scientific advances. The emergence of new instruments gave rise to a data-driven neuroscience allowing us to learn about the state of the brain supporting known mental functions and conversely. In parallel, the appearance of new mathematics allowed the development of computational models describing fundamental brain functions and implementing them in technological applications. While emphasizing the methodology of physics, the special issue aims to bring together these trends in both the experimental and theoretical sciences in order to explain some of the most basic mental processes such as perception, cognition, emotion, consciousness, and learning. In this editorial, we define unsolved problems for brain and psychological sciences, discuss possible means toward their respective solutions, and outline some collaborative initiatives aiming toward these goals. The following problems are defined in gradual order of difficulty: what are the universal properties of human behavior across conditions and cultures? What have each culture learned over historical times and why should specific elements of knowledge be accumulated over cultural evolution? Can computational psychiatry help predict, understand, and cure mental disorders? What is the function of art and cultural artifacts such as music, fiction, or poetry for the cognitive system? How to explain the relation between first-person subjective experience and third-person objective physiological data? What neural mechanisms operate on which mental content at the highest levels of organization of the hierarchical brain? How do abstract ideas emerge from sensory-motor contingencies and what are the conditions for the birth of a new concept? Could symmetry play a role in psychogenesis and support the emergence of new hierarchical layers in cognition? How can we start addressing the question of meaning scientifically, and what does it entail for the physical sciences?

Keywords: Physics of mind; Mind; Brain; Cognition; Cultural invariance; Sacred values; Cognitive technologies; Cultural evolution; Computational psychiatry; Neurotechnology; Emotion; Interoception; Consciousness; Symmetry; Hierarchy; Meaning

1. Introduction

In past decades, brain science has made tremendous progresses in its attempt to understand the organizational principles of information processing. From the hierarchical mechanisms of perception and cognition, to the role of emotions in the organization of neural assemblies, and the study of bounds on cognition and problem-solving: at nearly all levels of analysis, a wide range of experimental data offers a clearer understanding of the thinking brain

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and its living body. Despite tremendous progress, our understanding of basic functions such as learning, intelligence and consciousness rest upon vague concepts, which remain difficult to operationalize with precision. With the special issue, we aim to offer a step toward working collaboratively on these problems by providing a common language built upon stable definitions abstracted from reproducible experiments. With the advent of ubiquitous computing, artificial intelligence and their deployment in civil society, new questions concerning the very nature of natural intelligence come into the scope of empirical analysis [11,12]. The explosion in demographics and our increasing dependence on technology, are causing possibilities for human conflict to explode exponentially at a global scale. We need an in-depth understanding of human behavior that is coherent across disciplines, and new models for the principles underlying brain communication, interaction and self-control, these very same principles that allow life and knowledge to flourish and expand through culture.

In this editorial, we propose to outline eight fundamental problems, which remain unsolved and, in our opinion, demand pressing scientific attention. We divided these problems into two categories, easy and hard. Easy problems are essentially problems at the descriptive level of analysis. They are concerned with identifying invariant patterns in human behavior and explaining away the deviations observable in the case of psychiatric disorders and the differences observable in the large-scale societal organization of knowledge and cognition. Hard problems concern the rigorous measurement of concepts (e.g., emotions, interoception, consciousness) and the development of the appropriate technology for doing so. We present these problems in a gradual order of difficulty, and discuss eventual means toward their solutions. Finally, we conclude this article with some remarks concerning the mechanisms underlying brain growth, and the evolution of cognitive and cultural systems in the wild.

An emphasis has been placed on cultural processes and their underlying affective life, as culture is perhaps the domain of research where neuroscience meets its most interesting frontiers, and where applications hold the greatest transformative potential. This list is not meant to be exhaustive, but rather present the scope and the field of analysis of what has been referred to in recent years as the *physics of mind*. Physics is often regarded as the most successful area of science. It has even been argued that the methods of physics are the sole means for obtaining truth about the known universe, in the form of general laws that can be applied at all scales and sizes. In its current form, the span of physics covers a wide range of different areas: Newtonian mechanics describe celestial bodies, electrodynamics describe interactions at a small scale, astrophysics describes the nature of stars and interstellar medium, condensed matter physics teaches us the properties of matter, thermodynamics describes heat and help us build heat engines, biophysics enlighten our understanding of life and death and their origins on our planet. One peculiar object in the universe still pervades the scope of physics: the human mind, which generates physics. This begs the following question, is it possible to develop a physics of mind modeling accurately human cognition? Can science, and the scientists producing science, perceive perception, understand language, think cognition, and model that which models? Physics of mind differs from other attempts to understand the brain in its aims and methodology. This methodology is organized in three stages:

- Define few fundamental laws approximating a broad physical area, and propose their mathematical or diagrammatic formulations.
- Based on these fundamental laws build a theory for this area of knowledge, which does not contradict any known fact and predicts *new* nontrivial and experimentally verifiable phenomena.
- Conduct experiments to prove or disprove the theory.

In past decades and due to large funding programs, such as the Brain Research through Advancing Innovative Neurotechnologies (BRAIN) initiative and the Human Brain Project, a manifold of mental phenomena has been explored, including brain functions such as perception, attention, memory, learning, emotion, and language. Successful technological applications such as brain-computer interfaces and other neurotechnologies have been devised [5]. These advances have been paralleled by trends in the biomedical and clinical sciences, concerned with designing a more reliable psychiatry. For example, the Research Domain Criteria by the NIMH is a research framework for new approaches to investigate mental disorders [19]. In order to explore the basic dimensions of functioning that span the full range of human behavior from normal to abnormal, this framework integrates many levels of information (from genomics and circuits to behavior and self-reports). The goal is to understand the nature of mental health and illness in terms of varying degrees of dysfunctions in general cognitive systems. However, these frameworks lack unifying principles and deep models for general cognitive systems. Physics of mind can bring fundamentally new insights to these endeavor by providing simple models for basic cognitive functions and offering predictions explaining away signs and symptoms, paving the way for new technological applications and treatments avoiding the severe side effects associated to the existing chemical and electrical treatments. After two years of curation, we hope that the special issue can contribute to these collective endeavors by providing parsimonious explanations to make sense of large amount of experimental data and pave the way toward truly transcultural brain and behavioral sciences.

2. Easy problems: invariant patterns in human behavior

We start by listing some easy problems for cognitive neuroscience. These easy problems essentially depend on descriptive studies to identify invariance in human behavior at a global scale. One of the major drawbacks in this regard is the lack of heterogeneity in psychological data and the issue of reliability of the existing data, meaning the problem of reproducibility. To address these issues, collaborative projects founded on principles of open science such as Neurosynth from Tal Yarkoni, Brainbox from Roberto Toro in Paris, Mindlogger and the Healthy Brain Network from the New York Child Mind Institute and other collaborative participatory science [20,21,36], coupled with cheap accessible technologies and open linked data, can accelerate the collection and communication of data and ideas to identify invariant patterns across human cultures. One key notion introduced for this purpose is human sacred values, which play a critical role in decision making. Identifying sacred values across human cultures, their coherence and contradictions is a fundamental challenge for the physics of mind. In terms of neurobiology, sacred values correspond to the mental representations at the highest hierarchical levels of the mind-brain, which evolve to unify all lower level representations and our life experience. Cultural artifacts allowing events of shared attention and collective emotions can reveal a great deal about sacred values and their importance for cognitive and cultural systems. New tools such as computer simulation and network analysis are also useful to provide insights, as reviewed in this special issue in [4] and [5]. However, the scientific definition of human sacred values generates many methodological, theoretical, and ethical difficulties.

2.1. Cultural invariants

Problem 1: invariant patterns of behavior across human cultures.

What fundamental similarities across human cultures exist, and are there fundamental differences? One of the oldest and most important problems for the science of mind is to identify trends and patterns across human cultures at a global scale [22–24]. Living organisms and their surrounding niches are fitted to their environment, and reflect the constraints imposed by their physical, biochemical and social milieu [8]. A large body of work in anthropology has demonstrated differences in morphology across climates [25], however it remains difficult to assess fundamental similarities and differences in terms of psychological functions. One of the most important brain functions for life is learning [8–10]. However, our current psychology is still lacking a clear definition for the learning process, which could be applied across scales and predict for cultural invariance. One of the essential tasks for the physics of mind will be to devise new empirical and theoretical tools to learn about learning, which can be applied transculturally. As mentioned, one essential notion proposed for the study of cultural learning is sacred core values [37,39]. Sacred values are a challenge for standard economic models, as they are immune to material tradeoff [37]. They are fundamentally related to the high-level cognitive content described below (section 5) and their underlying emotions. Addressing the issue of invariant patterns in behavior across human cultures should offer new perspectives on challenges such as global warming, global inequalities, and global mental health. Furthermore, it may help us achieve global peace and accelerating the success toward the 17 sustainable global goals set by the United Nations General Assembly in 2015 for the year 2030. Sacred values are the cornerstone of cultural evolution and play a key role in cultural conflict [38]. A better understanding of the psychophysiology of the emotions underlying sacred values and their fundamental relation to learning across cultures, could therefore provide new insights for mitigating violent conflict and managing peacekeeping operations. Computer simulations hint toward differences between two fundamental kinds of human cultures: traditional and innovative [26]. This mirrors the distinction in cultural psychology between tight and loose culture [27]. It has been suggested that these differences are reflected in the emotionality of these cultures, which in turn reflects in the evolution of linguistic features [26].

2.2. Culture growth

Problem 2: mechanisms of cultural growth.

How does culture grow? How do cultures avoid so-called catastrophic interference? What have each culture learned over history, what specific elements of knowledge have they accumulated over cultural evolution and why? What can this teach us about the rate of evolution of cultures? Are there fundamental bounds on cultural learning rate? As demonstrated by Ramstead and colleagues in this special issue, the physics of mind and its variational ecology can offer new theoretical elements [8]. Humans are an anomaly in the animal realm, devoting a large portion of their time and energy on behavior that, at first sight, may not seem essential for survival. Since the very first ages of the species, we engage with passion into practices such as astronomy, paintings, music, storytelling, and mathematics. The affective life underlying these human practices plays an important role within the existence of an individual, providing evidence for a shared sense of belonging and purpose. Physics of mind suggests that these emotions play a fundamental role in the evolution of culture and the preservation of cognition. For example, music has been shown to help the cognitive system overcome cognitive dissonance [42]. Peak learning emotions triggered by collective narratives such as psychogenic shivers or aesthetic chills have been proposed to help the cognitive system deal with fundamental cognitive dissonance (where both elements of the contradiction are equally resistant to change), by providing new artificial content to overcome the contradiction [43]. Cultural growth depends on the accumulation and creation of knowledge, and its rate is conditional on the design of tools and technologies extending this function (symbols, books, computers). The term cognitive gadget has recently been put forward by Cecilia Heyes to describe such tools [40]. A substantial amount of work has been done on this question by scientists as diverse as Otto Wiener, Otto Neurath, Ernst Kapp, Ernst Mach, Herbert Spencer, and Charles Sanders Peirce [41]. How do cognitive tools perform their function and how do they interface with the brain and body? What predicts the appearance of cognitive technologies at a given point in the culture? What will be the long-term effects of the democratization of computers in human societies? How should computer and human-machine interfaces be designed to best fit the specificities of the human mind and its living body? Will computers be able to interface with our affective and introspective abilities? As we underlined in [41], cognitive tools *satisfy natural curiosity* and aesthetic emotions are a measure of this process.

2.3. Cultural artifacts

Problem 3: function of cultural artifacts for cognitive and cultural growth.

Brain scientists have been closely interested in art and its effects on the human brain. Phenomenon such as music [47,42], stories [51], architecture [52], dance [48,49], poetry [46], and films [50,43] have received empirical attention despite the complexity inherent to these cultural artifacts. In fact, the interest of mind scientists for art is as old as psychological science itself [53–55]. Mathematical models and computer simulations attempting to reproduce the creative process have lead to general theories of how humans construct meaning out of invariant patterns in their environment [56,57,16,58]. Given their prevalence across human societies [55] at all temporal scales [59], it has repeatedly been suggested that cultural artifacts such as songs, stories, poems may serve a general purpose of prime importance for the human animal. One hypothesis, that has been tested across artistic domains and human cultures, is the possibility that these stimuli may help maintain the cognitive system coherent and overcome contradictions inherent to evolution and learning new facts about the meaning of life and the universe [16,43]. This raises two fundamental questions as to (a) what the elements of these contradictions may be in various cultures and across phenotypes, and (b) the process by which these contradictions are overcame by a cognitive system with the assistance of cognitive technologies. It has been suggested that the creation of new cognitive content (i.e., the birth of a new layer in the cognitive hierarchy and novel more general ideas encompassing both elements of the contradiction) may be a possible mean for the cognitive system to maintain its unity. Empirical evidence has shown that music may help maintain the cognitive system coherent [42]. The term *psychogenics* may be appropriate to describe the genesis of new mental models within the cognitive hierarchy. A detailed study of emotions associated to psychogenesis may reveal both the cognitive contradictions underlying cultural evolution and the neural mechanisms of conflict resolution at the highest levels of the cognitive hierarchy (see e.g., [17]). However, the anatomical and physiological underpinnings of this resolution of contradiction are still unknown. Furthermore, a large portion of these aesthetic emotions are unconscious, which slows down the rate of their scientific study [34]. In this volume, we discuss these emotions beyond the threshold of language and consciousness and their role in cognition, language comprehension, and decision-making [34].

2.4. Origins of mental disorder

Problem 4: computational psychiatry and top-down effects on behavior

Identifying cultural patterns and heterogeneity in knowledge and high-level cognition should pave the way toward designing the right psychiatry for addressing critical issues in global mental health, and the significant worsening of the burden of mental disorders at the global scale [60]. In this regard, one must mention the excellent work of Kirmayer and colleagues on transcultural psychiatry ([62], see also in this volume 10). Describing and understanding the highest levels within the hierarchical brain-mind should lead us to understand how the rest of the structure relies on top-level for predictions and behavior regulating uncertainty. This attempt of making sense of mental disorders in terms of adaptive function and principles of brain organization is sometimes referred to as computational psychiatry [61]. The role of top down predictions for the cognitive brain has been demonstrated empirically in [31] and [32]. In this volume, George Ellis lists and emphasize the top down effects on the brain, where lower level elements are adapted to perform their higher-level functions [1]. Conscious aesthetic emotions, such as those elicited by high-level conscious cognitive inference, can foster the emergence of a more scientific and reliable computational psychiatry predicting for such disorders as hallucinations, paranoia, phobias, mood disorders, within a unified parsimonious model of the biological mind, its living body and social ecology [29]. Recent endeavor such as the Research Domain Criteria within the National Institute of Mental Health [30] are aiming for a more dimensional psychiatry taking into account human behavior at all scales (from genotype to phenotype, including social dimensions). Could we predict beforehand dysfunctional behavior at the highest-levels through detailed studies of conscious learning emotions and their somatic markers? In this volume, Arturo Tozzi argues on the basis of his multidimensional brain theory that the principle "higher dimension, greater information" may explain the occurrence of mental activities and elucidate some mechanisms associated with dimensionality reduction [7]. The research field of human interoception (i.e., the synthesis of internal sensory signals and its role in higher level cognition) is highly promising in terms of its applications to technology for mental health [63,64]. Somatosensory interfaces open new pathways for clinical applications by augmenting or modulating interoceptive inferences and, in the present volume, we present results from interoceptive technologies producing effects on empathy, pleasure, and high-level cognition [33]. Somatosensory interfaces provide a novel method for affective neuromodulation by stimulating the body in a controlled way. How is this information integrated within interoceptive processing? What happens when you engage emotional pathways with controlled stimulation or amplify the sensory signals as a basis of interoceptive predictions? These questions and their answers can help refine the existing models of human emotion, interoception, and consciousness. They may provide new quantitative models for psychophysiology, theoretical neurobiology, and computational psychiatry. In terms of affective neuroscience, somatosensory interfaces offer a unique opportunity to study the mechanisms of salience detection and the consequences of conscious body perception on behavior and decision-making. Reliable non-invasive treatments for interoception-related mental disorders can be researched in novel forms.

3. Hard problems: testing fundamental theories

Hard problems depend on the development of precise technology to measure basic mind mechanisms such as learning or emotions, in order to test fundamental theories and derive meaningful definitions for terms such as consciousness, attention, and interoception. The most difficult problems in our opinion are those at the interface between science and philosophy, where truth meets meaning. These problems concern the nature of human semantics and their relevance not only for (linguistic) communication, but also at a larger physical scale, in terms of our fundamental need for knowledge and cognition. Some hints are proposed to start investigating empirically the issue of meaning and consciousness.

3.1. Engineering human emotions

Problem 8: Engineering human emotions to extend the scope of introspection

Neuroscience cannot elude the problem of first-person experience and the gap between first person subjective data (introspection) and third person objective data (extrospection). Recently, the field has turned toward the notion of interoception, and interoceptive inferences, for answers [33]. Research on human interoception (i.e., the aggregation of neural signals) has the potential to unite fields of research as diverse as studies of somatic and affective disorders, metacognition, neurophenomenology, and neuromodulation. In this issue, Boris Gutkin and colleagues review the current computational theories of homeostatic control [2] and Luiz Pessoa emphasizes the key role of emotion networks in the emergence of intelligence [12]. This trend in interoceptive neuroscience is paralleled with an increasing tendency to explain emotions, feelings, moods and their respective disorders in terms of their underlying biological functions [35]. It has been suggested for example that major depressive disorders may hold an adaptive function related to problem-solving and the processing of uncertainty [66]. Interoceptive neuroscience offers a unique vantage point for the study of how bodily activity gives rise to emotions, consciousness and a sense of self. Can we engineer human sensations to produce reliable effects on cognition and enhance interoception and introspective abilities? This is the topic approached by [33] presenting recent data on emotion engineering through targeted bodily interventions. Consciousness developed in the course of biological life to allow greater and fine control over animal behavior. It is still an open question as to how unconscious sensory-motor regulation becomes conscious and a major challenge for future neuroscience [45]. Conscious *feelings* are thought to emerge from interoceptive activity and bodily changes. Consciousness stems from the need to evaluate the models synthesizing unconscious noisy sensory-motor signals. In other words, metacognition is inference about one's ability for control and consciousness is a measure of the body self-monitoring its activity [67]. Can we engineer new (synthetic) emotions? Can we create new learning qualia rendering unconscious processes amenable to consciousness? In [34], we suggest that new unconscious emotions may be generated, allowing science and technology to enhance the field of conscious thought.

3.2. Top-level cognition

Problem 5: mental models at the highest levels of the cognitive hierarchy.

What is most important for a cognitive system and how does it devise long term goals? Conscious *aesthetic emotions* (generally understood as feelings of awe, beauty, sublime, meaning) underly the discovery of new fundamental elements of knowledge and can be used as a probe to study the highest levels of cognition. It has been suggested that these emotions developed over the course of evolution for the purpose of pattern recognition and the cognitive evaluation of sensory signals [44]. The notion of an aesthetic emotions can be generalized to describe the process binding perception and cognition, for improving action capabilities. Aesthetic emotions allow perception to evolve over time, and refine cognitive systems. Most aesthetic emotions are unconscious and occur each time we recognize an object in our surroundings. When we encounter an object that we fail to recognize, or that presents fundamentally new features, we may feel aesthetic emotions consciously, these may be positive and pleasurable or negative and unpleasant. Conscious access to liminal aesthetic emotions derives and depends from the scope of the cognition involved in the process [28]. We become aware of our learning processes only when a change is important enough that it may affect the cognitive system as a whole and transform behavior at a significantly. The content of conscious aesthetic emotions at the highest levels of the cognitive hierarchy represents what matters most to humans. What are the physiological mechanisms regulating learning for life and the highest models of the mind-brain? What is at the very top of the cognitive hierarchy? How many models are at the very top and what happens when they evolve through behavioral change? What new methods and technologies can we devise to study high-level cognition and conscious aesthetic emotions?

3.3. The genesis of ideas

Problem 6: The genesis of new ideas and the emergence of new layers in cognition.

What are the necessary and sufficient conditions for the emergence of a new layers of thought within a cognitive hierarchy? This problem has long been referred to in psychology as cognitive development, or intellectual development and has attracted the attention of key theoreticians such as William James, James Sully or Jean Piaget. Cognitive development has now become a field of study of its own, with applications in the clinical and educational sciences. However, the psychophysiological problem of the emergence of abstract ideas, and the underlying biochemical processes remain extremely difficult to approach quantitatively. This difficulty is in part due to the lack of protocols and markers for cognitive growth. In this issue, Heuer and Toro examine the role of mechanical morphogenesis in the development and evolution of the neocortex, and suggest to revisit that the importance of mechanical morphogenesis for neocortical evolution has been underestimated [3]. How do new abstract ideas emerge and what biology underlines the birth of new ideas and human creativity?

3.4. Symmetry and mind growth

Problem 7: Does symmetry play a role in cognition?

We are only starting to uncover the extraordinary ability of brain to self-organize and build autonomously new hierarchical cognitive layers on top of models acquired through experience to anticipate future consequences of its actions over a wider spatio-temporal range than immediately available to the senses. I would like to take the opportunity of this issue to suggest a working hypothesis concerning the underlying computational mechanism. Judging by the striking ubiquity of antagonisms across abstract concepts (e.g., truth and falsity, right and wrong, bright and dark, knowledge and ignorance, bravery and cowardice), perhaps *the organizational principle of symmetry* may be crucial for describing and understanding cognitive growth. Symmetry, just as hierarchies, are ubiquitous in nature as an organizational principle allowing simple systems to grow into more complex stages [69,70]. Chirality is a specific type of symmetry. Recent advances in mathematics, physics, and biochemistry suggest that chirality, chiral synthesis, may play a crucial role in the emergence of new hierarchical layers in a complex structure. As suggested in the work of Vsevolod Tverdislov, chirality may play a role as an instrument of stratification of hierarchical systems [68]. The principle of *hierarchy* has been useful to make sense of the organization of perception and brain organization [17]. However, the notion of *symmetry* has never been used for the description of mind. Could symmetry help describe the emergence of new hierarchical layers in thought? Could the notion prove useful to make sense of dual antagonisms in thoughts and the role of binary oppositions in our abstract models of the world? Could symmetry describe and explain how new hierarchical layers in cognition aggregate lower (antagonistic) levels in the genesis of meaning?

4. Conclusion

The history of brain and cognitive sciences lead to several fundamental principles for behavior, which have been verified across life, such as the Weber laws [6], which quantifies the perception of differences between stimuli and has been demonstrated to hold even in lower animals [13]. A complete review of such psychophysical laws is presented in this volume by Ihor Lubashevsky [6]. More recent theories, such as homeostatic reward learning or cognitive dissonance have been mathematically modeled and demonstrated in computer simulations [2]. New unifying principles have emerged, such as the free energy principle [9], the simplicity principle [14], adaptive resonance theory [15], dynamic logic and the knowledge instinct [16]. These basic theories aim to predict the widest range of empirical data using as few descriptive elements as possible [17]. In this sense, these endeavors are closing the loop of psychological and brain science, which historically emerged from the work of such physicists as Weber, Helmholtz, Mach, or Wertheimer [18]. Perhaps, the most perplexing interrogation to emerge with the physics of mind concerns human meaning sprouting in a physical universe. How can we start to approach the question of meaning scientifically, and what does it entail philosophically? In his essay titled "The Boundaries of Scientific and Philosophical Concept-Formation" [65], the admirable Moritz Schlick, founder of the Vienna Circle, suggested that science is about finding the *truth* about the world, where philosophy is about clarifying the *meaning* of such truth. According to Schlick, science and the scientific method unravel the truth about the known universe. Scientists organize human propositions about the nature of reality in the form of parsimonious mathematical laws, as he who wants to go far only takes what is necessary. The function of philosophy is to clarify the meaning of these laws, not to invent its own independent principles. As a consequence, there cannot logically be any experimental philosophy. Rather, the philosopher is Nature's hermeneut and when he fails to his task, the whole of society suffers a crisis. The world appears shallow and empty while science is blindly revered. Now that the very problem of meaning penetrates the domain of science, as psychology rejoins its roots in the physical sciences, it is our hope that philosophy may meet its origins in the realm of wisdom while meaning rises as the new frontiers of knowledge.

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