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Meeting report

Next frontiers in consciousness research

Biyu J. He[1,*]
[1]Neuroscience Institute, Departments of Neurology, Neuroscience & Physiology, and Radiology, New York University Grossman School of Medicine, New York, NY 10016, USA
*Correspondence: biyu.he@nyulangone.org
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Consciousness science has matured over the past three decades and is currently on the cusp of explosive growth, with the potential to transform medicine and technology. The global community recently met to synthesize the current state of knowledge and define the most exciting approaches to advance the field.

INTRODUCTION

The origin of conscious awareness is one of the oldest and deepest mysteries in philosophy and science. Our vivid experiences of the world, of interacting with others, of joy and pain, of contentment and agony are what make life worth living. No normal humans would be willing to trade their conscious experiences for better capabilities and higher intelligence if they were unable to subjectively experience the world.

The brain mechanisms of conscious awareness have become an urgent topic due to the rapid development of artificial intelligence, which has prompted calls to develop a better scientific understanding of consciousness so that scientists and engineers are better equipped to assess the potential emergence of sentience in machines (https://amcs-community.org/open-letters/). Beyond machine consciousness, the existence and quality of consciousness in various animal species and in early human development are topics that not only stoke great curiosity and controversy but also wield enormous power in shaping public policy.

Recently, at a 3-day workshop held at the NIH, global experts from different sub-disciplines relevant to consciousness research gathered together to synthesize the current state of knowledge, discuss approaches to test existing theories of consciousness, and develop a roadmap for future discoveries in the science of consciousness. Recordings of all 3 days can be found on the NIH website (day 1: https://videocast.nih.gov/watch=49160; day 2: https://videocast.nih.gov/watch=49162; day 3: https://videocast.nih.gov/watch=49164).

CONTEMPORARY CONSCIOUSNESS SCIENCE AND MOTIVATIONS FOR THE MEETING

While philosophers since the dawn of human civilization have pondered the nature of consciousness, systematic inquiries into its properties and substrates have only become possible with the arrival of modern psychology and neuroscience around the turn of the 20th century. Even then, several issues have made the study of consciousness especially tricky.

First, probably more than any other topic in psychology, everyone has their own intuitions about how consciousness should work; after all, it is the most intimate and subjective phenomenon. These folk psychological intuitions, often with dualist tendencies, pose significant challenges to rigorous scientific pursuits.

Second, the term "consciousness" has been used in a variety of ways both in scientific literature and in lay dialogue, referring to concepts as varied as subjective awareness, responsiveness, and moral values. As such, skeptics of consciousness research often protest that there is no clear definition of consciousness. However, the core scientific field has soundly coalesced on the definition of consciousness as "subjective awareness." which has guided the field's rapid progress over the past three decades.

Third, because conscious awareness is an inherently subjective phenomenon, subjective reports by human participants are typically necessary for experimental investigation. The extent to which an investigator can trust participants' subjective reports has been a long-standing debate in psychological studies of consciousness. However, seminal studies showing that people normally have good introspective access to their contents of awareness helped pave the way for modern neuroscientific studies of consciousness, which largely rely on subjective reports or their surrogates.[1]

Despite these challenges, consciousness science has matured by leaps and bounds. It is entering into a coming-of-age moment, as evidenced by the sustained growth of the Association for the Scientific Study of Consciousness and increasing interest in the neural bases of consciousness from the broader scientific community. With the support of the Division of Behavioral and Cognitive Sciences at the US National Science Foundation, as well as the Blueprint for Neuroscience Research and the NIH BRAIN Initiative at the US National Institutes of Health, a meeting was convened in June 2023 (https://sites.google.com/view/consciousness2023) to address a number of urgent questions.

1. What is the current status of our understanding of the neural bases of conscious awareness in humans?
2. Do different aspects of conscious awareness, such as percepts, wills, memories, emotions, and thoughts, share a set of core principles in their underlying mechanisms?
3. How do we synergize between research on *contents* of consciousness and *states* of consciousness?
4. How do we approach evaluating consciousness in nonverbal agents, such as non-human animals, fetuses and infants, and machines?

5. What role should theories play in our efforts to decipher the neural bases of consciousness, and what are the most fruitful empirical approaches?

TOPICS COVERED AND MAJOR DISCUSSIONS

Theories and general approaches to studying consciousness

Two prominent theories of consciousness out of several leading ones[2] were represented at this workshop. These included the Global Neuronal Workspace (GNW) theory[3] represented by Stanislas Dehaene and the Integrated Information Theory (IIT)[4] represented by Giulio Tononi. A major disagreement between these theories was whether consciousness is tightly coupled with cognitive functions such as working memory (GNW's position) or whether it is mainly phenomenology (i.e., subjective experiences) that does not serve any overt functions (IIT's position). These alternative views have been termed "functionalist" or "non-functionalist" views of consciousness, and this debate was far from being settled by this workshop. However, there were useful cross-disciplinary discussions on this topic. For example, Liz Phelps shared data showing that threats learned without awareness are quickly forgotten, while those learned with awareness are remembered for much longer. Therefore, the conscious and unconscious processing routes in the brain do appear to have widespread functional differences. Other examples include consciously perceived information having privileged access to working memory and long-term memory as well as conscious perception facilitating inhibitory control.[5] It remains to be seen whether these are quantitative or qualitative differences and whether consciousness is always coupled with function.[6]

A considerable amount of time in the theory session was spent on discussing the preliminary outcomes of an adversarial collaboration between GNW and IIT, where the international consortium had released their initial results days before the workshop.[7] This first set of results challenged both theories, as neither theory had all their predictions fulfilled by the data. The theorists discussed the methodologies employed in the experiments and potential ways to improve them. However, a major takeaway from the discussions in this session was that not only experimental approaches for studying consciousness need to be refined, but the theories themselves need to be improved, with room for new theories to be developed.

Finally, a strand of discussion that continued across the 3 days was whether the prevailing empirical approach to studying consciousness—namely, to identify the "neural correlates of consciousness" (NCCs)—is the most fruitful approach. One talk on conscious perception presented data showing that the neural correlates of conscious perception, at least as conventionally conceived (such as spatial/temporal localization), could vary significantly depending on contextual factors such as stimulus conditions and initial brain states prior to sensory input. In addition, multiple talks raised concerns that finding "minimally sufficient" neural mechanisms for a conscious experience (the definition of an NCC) may not be possible because there are many enabling factors (e.g., suitable brain states) and non-conscious antecedents (e.g., activity preceding conscious recall or spontaneous thought) that are required for inducing the experience. Proposed alternative solutions included identifying the full, causal mechanisms underlying a conscious experience[8] and systematically investigating how non-conscious processes give rise to and are influenced by conscious processes.

Conscious awareness of external sensory information

Several talks addressed the neural mechanisms of conscious perception, with a focus on visual awareness. Speakers presented compelling examples of neural activity that predicted the changing content of conscious awareness. These included single-unit neuronal firing in humans and macaques as well as population activity recorded by human neuroimaging in paradigms that carefully dissociate perceptual awareness from the physical sensory input. The presented findings revealed widely distributed neural correlates of conscious perception across sensory and associative cortices.

In addition, two talks saliently illustrated limits of conscious awareness, showing inattentional blindness of the presence or absence of color in the visual periphery and our lack of awareness about eye movement patterns. For example, saccadic eye movements during binocular rivalry of orthogonally moving gratings go in the direction of a weighted average of the two moving gratings, whereas awareness alternates all-or-none between the two moving gratings.[9] These observations spurred vibrant discussions. First, given that eye movement patterns do not always provide a faithful readout of conscious perceptual content and, in some cases, are strongly dissociated from it, the consensus was that the use of "no-report paradigms"[10] needs to take these cautions into account. Second, a consensus view emerged from a discussion on the best paradigm to study conscious perception that emphasized diversity in experimental paradigms as a major strength and highlighted the variety of visual illusions developed over the years as providing a fountain of fruitful approaches for investigating the neural bases of conscious perception.

Finally, there was great interest in the question of whether there is a common set of neurobiological principles for different types of conscious awareness (e.g., self-awareness vs. perceptual awareness). This was acknowledged to be an open question that should be addressed by further empirical research. Nonetheless, there was broad agreement that the neural basis of perceptual awareness, which is one of the best developed subfields of consciousness research, holds potential to inform other topics of consciousness studies.

Conscious awareness of internally generated information

Awareness of internally generated information, including spontaneous thoughts, volitions, and recalled memories, forms a second pillar of the contents of our daily conscious awareness. These topics have been traditionally investigated in separate fields, yet several common themes emerged from the presentations. First, the default mode network appears to be a key player in both spontaneous thoughts and conscious memory recall, which is not surprising given that recalled memories are a major constituent of spontaneous thought. Second, neuronal firing ramps up 1–2 s prior to both memory recall (in the medial temporal lobe) and volitional actions (in the supplementary motor area). Third, the inferior parietal lobule (IPL), including the angular gyrus, supports both the generation of conscious movement intention and the construction of first-person reliving of a recalled experience. At present, it is unclear whether the computational circuits in the IPL supporting these divergent experiences are the same or different.

Some major questions remained unanswered. First, like in conscious perception, the threshold mechanism determining whether internally retrieved memory information reaches awareness remains elusive. One possibility emerging from the discussions is that this mechanism is implemented in the intricate interactions between hippocampal activation, reinstatement in sensory areas, and integrating or monitoring activity in associative areas such as the angular gyrus. Second, whether the threshold mechanism determining the success or failure of conscious awareness is similar or different between perception, memory, and volition remains unknown.

Feelings and emotions

Two radically different views about the genesis of feelings and emotions were presented. First, Antonio and Hanna Damasio presented a theory proposing that consciousness is provided by the continuous presence of homeostatic feelings, which inform the mind of the problems, needs, and opportunities arising from the bodily states (e.g., fever, nausea, thirst, hunger, or well-being). Under their hypothesis, homeostatic feelings are constructed by the interaction between the interior of the body and the nervous system, mediated by slow, unmyelinated or poorly myelinated axons, and with the central relay nuclei in the posterior brainstem playing a major role. This system is not fully insulated by the blood-brain barrier, allowing molecules including monoamines and neuropeptides circulating in the blood to directly influence interoceptive feelings.

A very different hypothesis was described by Joseph LeDoux. LeDoux presented a version of a higher-order theory of consciousness that suggests that all conscious experiences, including emotions and feelings, result from higher-order mental states that likely reside in the prefrontal cortex. These higher-order mental states reflect upon the contents of first-order states, which were in turn represented in lower-level cortical areas. Whether conscious feelings and emotions primarily result from survival-relevant functions carried out by the archaic brainstem circuits or by higher-order cognitive functions residing in phylogenetically newer areas of the cerebral cortex will be a key question for future empirical research to answer.

Encouragingly, a range of intriguing empirical findings were also presented in this session, including optogenetic studies in mice showing that externally imposed tachycardia induces anxiety-like behavior[11] and human psychophysical studies revealing the intricate roles that awareness can play in fear conditioning.

Consciousness during early development and in animal species

When do babies become conscious? Which animal species have sentient experiences? These questions intrigue every curious person and hold enormous consequences for societal policies. At the same time, they are extremely difficult to answer. Several talks addressed these thorny questions.

Regarding early development, two experts gave highly convergent views from neuroscientific and psychological perspectives. Both talks suggested that our conception of the newborn has changed dramatically in recent decades, and new scientific data suggest that the mental capabilities and brain functions of the newborn are vastly greater than previously believed. Ghislaine Dehaene-Lambertz placed the emergence of consciousness to be around 35 weeks of gestational age (wGA) because, at this point, the thalamus starts to drive the cortex continuously and the EEG shifts from burst-suppression patterns to continuous waves. Similarly, neural signatures for relatively complex sequence processing emerge around 35 wGA. Philippe Rochat likewise placed the emergence of awareness somewhere in the third trimester *in utero*. Dehaene-Lambertz also presented data showing that infants under 1 year of age have very slow EEG signatures for conscious perception, whereby a wave happening at 300 ms in adults is delayed until ~1 s ("a slow system but functional and conscious").[12]

A definitive answer about consciousness in animals is even more difficult. Jonathan Birch advocated for a theory-light research program whereby researchers identify cognitive abilities facilitated by conscious perception in humans and then look for similar patterns of facilitation in other animals. He showed data suggesting that trace conditioning, a phenomenon established in humans to be facilitated by awareness,[13] is similarly facilitated by awareness in fruit flies and honeybees. Although these data do not prove that flies and bees are conscious, they suggest that flexible, operational definitions that allow for gradations and ethologically appropriate application can facilitate progress in probing the existence and quality of consciousness in other animals.

States and disorders of consciousness

Two sessions were devoted to loss of consciousness under anesthesia and clinical conditions including epilepsy and traumatic brain injury. The anesthesia session presented the field's exquisite knowledge about the mechanisms of various anesthetic drugs acting on subcortical and cortical circuits and their effects on neural dynamics. There were some disagreements among speakers about how prevalent intraoperative awareness is and how well the current EEG-based methods are able to prevent it. Several key questions remain incompletely understood, including: to what extent do different states of unconsciousness recruit common neural pathways? Are there common principles that explain unconsciousness under different anesthetics that are associated with distinct cortical EEG patterns (e.g., propofol vs. ketamine)?

In the session on disorders of consciousness, speakers presented major advances over the past decades in using behavioral and EEG-based metrics to diagnose disorders of consciousness and measure the level of awareness in an uncommunicative individual. There were major discussions on the ethical issues involved, including the procedure for consenting and the respective roles of patients, relatives, and physicians. A major challenge identified, from both scientific and clinical perspectives, is the difficulty (or impossibility) to verify that someone is indeed unconscious, which is itself associated with profound ethical implications. Further, the exact sensitivity and specificity of the current diagnostic methods remain unknown. Finally, most of the current methods are centered on diagnosis in the here and now, while methods for prognosis are lagging behind.

CONSENSUS

Despite the wide-ranging topics covered in the workshop, a set of consensus points emerged.

First, there was broad agreement that the field should tackle the neural mechanisms of conscious awareness using a range of empirical, neurobiologically grounded approaches and, at least for the time being, welcome the possibility that different contents of awareness might not have shared principles. Comparisons and overarching principles should be sought across these different subdisciplines, in a theory-neutral, empirically grounded manner.

Second, there is an urgent need to develop paradigms that can be used to study consciousness in parallel in humans and non-human animals both behaviorally and neurobiologically. Relatedly, there is an urgent need to leverage multiple techniques across spatiotemporal scales, both correlative and causal, to investigate the neural mechanisms of conscious awareness.

Third, comparative studies between humans and a variety of animal species, including both mammals and non-mammals, using behavioral approaches involving nonverbal reports will be useful to shed light on the evolutionary origin of consciousness in modern animals.

CONCLUSIONS AND OUTLOOK

Interest in the neurobiological mechanisms of consciousness has increased exponentially. The stimulating talks in this workshop provided but a sample of the exciting science in the field. The diverse opinions and vibrant discussions from experts working on distinct subdisciplines, some of which traditionally have had little crosstalk, show the great potential for cross-fertilization and new ideas that commonly sprout when a new field becomes established. Many in the field credit Francis Crick and Christof Koch's work in the early 1990s for ushering in the modern era of consciousness research. Thirty years later, this workshop attempted to synthesize the knowledge gained during this period and to identify key questions and the most promising approaches to advance the field. It will be exhilarating to watch the field's developments over the next 30 years. Deciphering the neurobiological bases of conscious awareness in humans will not only allow us to evaluate consciousness in animals and machines but will also help to answer one of the deepest mysteries of our human experience.

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DECLARATION OF INTERESTS

The author declares no competing interests.

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