walking on level ground. More intense gaits like running, where the legs cycle more positive and negative mechanical power, and tasks like walking downhill, descending staircases, or decelerating to a stop all provide increased opportunities for exoskeletons to assist the body's biological brakes while generating electricity.

Next-generation exosuits will begin to integrate physiological sensing systems and machine-learning algorithms to increase the versatility and impact of wearable assistive devices. During the next decade, a new challenge may be to develop an exosuit that minimizes human metabolic energy expenditure on a round-trip course spanning many kilometers over many days with access to an onboard rechargeable battery while providing the user with a set amount of caloric intake per day. Optimal performance will likely require multijoint, hybrid support strategies that combine injection, extraction, and transfer of both electrical and mechanical energy to adapt continuously to locomotion-task demands and limit heat loss of the user.

Such devices could have several applications, such as extending the range of on-foot search-and-rescue crews, outdoor adventurers, or soldiers on humanitarian missions. In the developing world, an exosuit could provide between 20 and 40% of the electricity needed per person on a typical day. The energy demands of portable electronics and increased recognition of the role of movement in longevity may drive exosuits toward widespread adoption. ■

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HYPOTHESIS

Making the hard problem of consciousness easier

Championing open science, an adversarial collaboration aims to unravel the footprints of consciousness

By **Lucia Melloni[1,2], Liad Mudrik[3], Michael Pitts[4], Christof Koch[5,6]**

The history of science includes numerous challenging problems, including the "hard problem" (*1*) of consciousness: Why does an assembly of neurons—no matter how complex, such as the human brain—give rise to perceptions and feelings that are consciously experienced, such as the sweetness of chocolate, or the tenderness of a loving caress on one's cheek? Beyond satisfying this millennia-old existential curiosity, understanding consciousness bears substantial medical and ethical implications, from evaluating whether someone is conscious after brain injury to determining whether nonhuman animals, fetuses, cell organoids, or even advanced machines (*2*) are conscious. A comprehensive and agreed-upon theory of consciousness is necessary to answer the question of which systems—biologically evolved or artificially designed—experience anything; and to define the ethical boundaries of our actions toward them. The research projects described here will hopefully point the way and tell us whether any of today's major theories hold water or not.

After prosperous decades of focused scientific investigation zeroing in on the neural correlates of consciousness (*3*), a number of candidate theories of consciousness have emerged. These have independently gained substantial empirical support (*4*–*7*), led to empirically testable predictions, and resulted in major improvements in the evaluation of consciousness at the bedside (*8*, *9*). Notwithstanding this progress, the conjectures being put forward by the different theories make diverging claims and predictions that cannot all be simultaneously true. Moreover, the theories evolve and continue to adapt as further data accumulates, with hardly any cross-talk between them. How can we then narrow down on which theory better explains conscious experience?

The road to a possible solution may be paved by means of a new form of cooperation among scientific adversaries. Championed by Daniel Kahneman in the field of behavioral economics (*10*) and predated by Arthur Eddington's observational study to test Einstein's theory of general relativity against Newton's theory of gravitation (*11*), adversarial collaboration rests on identifying the most diagnostic points of divergence between competing theories, reaching agreement on precisely what they predict, and then designing experiments that directly test those diverging predictions. During the past 2 years, several groups have adopted this approach, following an initiative that aims to accelerate research in consciousness. So far, several theories of consciousness are being evaluated in this manner to test competing explanations for where and when neural activity gives rise to subjective experience.

The global neuronal workspace theory (GNWT) (*4*) claims that consciousness is instantiated by the global broadcasting and amplification of information across an interconnected network of prefrontal-parietal areas and many high-level sensory cortical areas. The sensory areas carry out different functions that range from feature processing to object or word recognition. Information in those sensory areas is processed in encapsulated modules, remaining unconscious. The frontal-parietal networks support integrative and executive functions, including selective attention and working memory. According to the GNWT, a stimulus must be attended to trigger activity that helps distribute this sensory information to many parts of the brain for further processing and report. It is this global broadcasting across many modules of specialized subsystems that constitutes consciousness. Conversely, the integrated information theory (IIT) (*5*) holds that consciousness should be understood in terms of cause-effect "power" that reflects the amount of maximally irreducible integrated information generated by certain neuronal architectures. On the basis of mathemati-

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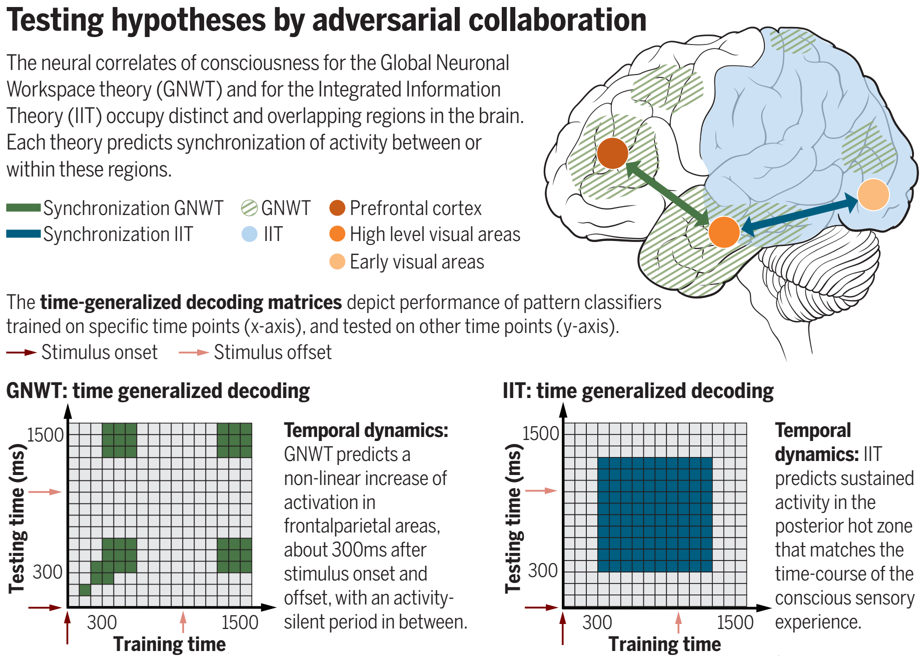

cal and neuroanatomical considerations, the IIT holds that the posterior cortex is ideally situated for generating a maximum of integrated information. In this theory, consciousness is not input-output information processing but the intrinsic ability or power of a neuronal network to influence itself. That is, the neuronal substrate of consciousness perpetuates itself for as long as the experience exists. The more cause-effect power a system has, the more conscious it is. For the IIT, the content of an experience is a structure of causes and effects (integrated information), whereas for the GNWT, it is a message that is broadcast globally.

Another controversy occurs between first-order (*12*, *13*) and higher-order (*6*, *14*) theories of consciousness. The former claims that reverberating activity in sensory areas suffices for consciousness, whereas the latter claims that a second, higher-order brain state must represent or "point at" these first-order sensory activations for them to be consciously experienced.

Both controversies are the types of theoretical disagreements that are currently being empirically tested by use of the adversarial collaboration approach. One of these collaborations, the COGITATE consortium (Collaboration On GNW and IIT: Testing Alternative Theories of Experience), is collecting data and has recently released a detailed preregistered report that outlines the methods, predictions, and planned analyses (https://osf.io/mbcfy). These experiments were designed by neuroscientists and philosophers who are not directly associated with the theories but are in close collaboration with advocates from each theory. The experiments are being conducted in six independent laboratories. Briefly, one of the experimental designs involves an engaging video game with seen and unseen stimuli in the background to determine whether neural correlates of the visual experience are present irrespective of the task. In another experiment, stimuli are shown for variable durations to investigate for how long the neural correlate of the visual experience exists. Neuronal activity in human subjects is measured with both invasive and noninvasive methodologies, from functional magnetic resonance imaging and simultaneous magnetoencephalography and electroencephalography to invasive electrocorticography, and is integrated across methodologies to test the theories' predictions. These focus on two key questions: Where are the anatomical footprints of consciousness in the brain: Are they located in a posterior cortical "hot zone" (*15*) advocated by the IIT, or is the prefrontal cortex necessary (*4*) as predicted by the GNWT? And, how are conscious percepts maintained over time: Is the underlying neural state maintained as long as the conscious experience lasts, in line with the IIT, or is the system initially ignited and then decays and remains silent until a new ignition marks the onset of a new percept, as the GNWT holds (see the figure)? Once the brain data are collected and analyzed, they will be made available to anyone. Relying on adversarial dialogue and collaboration, open science practices, standardized protocols, internal replication, and team science, these initiatives aim to promote empirical progress in the field of consciousness and to change the sociology of scientific practice in general.

Solving big questions may require "big science" because such questions are more likely to be solved in unison rather than through isolated, parallel, small-scale attempts. The adversarial collaboration approach builds on the success of large-scale collaborative institutes (such as the Allen Institute for Brain Science), and projects such as the Human Connectome Project, or the International Brain Laboratory in neuroscience, which were preceded by initiatives in physics such as the Large Hadron Collider at the European Organization for Nuclear Research (CERN) or the Laser Interferometer Gravitational-Wave Observatory (LIGO) experiment. With this series of adversarial collaborations, neuroscientists will get closer to understanding consciousness and how it fits into the physical world while improving scientific practices along the way. As for the initial theories undergoing this approach, it may be that neither the GNWT nor the IIT are quite correct. No matter the outcome, the field can use the results to make progress in framing new thinking about consciousness and testing other potential theories in the same way. The problem of consciousness will surely remain difficult, but understanding the ancient mind-body problem will become a little bit easier. ■

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