ASSOCIATION FOR PSYCHOLOGICAL SCIENCE

Perspectives on Psychological Science
2022, Vol. 17(4) 1150–1165

DOI: 10.1177/17456916211029942
www.psychologicalscience.org/PPS
SAGE

Where's My Consciousness-Ometer? How to Test for the Presence and Complexity of Consciousness

Tam Hunt[1], Marissa Ericson[2], and Jonathan Schooler[1]
[1]Department of Psychological and Brain Sciences, University of California, Santa Barbara, and [2]Department of Psychology, University of Southern California

Abstract
Tools and tests for measuring the presence and complexity of consciousness are becoming available, but there is no established theoretical approach for what these tools are measuring. This article examines several categories of tests for making reasonable inferences about the presence and complexity of consciousness (defined as the capacity for phenomenal/subjective experience) and also suggests ways in which different theories of consciousness may be empirically distinguished. We label the various ways to measure consciousness the *measurable correlates of consciousness* (MCC) and include three subcategories in our taxonomy: (a) neural correlates of consciousness, (b) behavioral correlates of consciousness, and (c) creative correlates of consciousness. Finally, we reflect on how broader philosophical views about the nature of consciousness, such as materialism and panpsychism, may also be informed by the scientific process.

Keywords
consciousness, philosophy of mind, psychometer, empiricism

How can we know if any person, animal, or anything is actually conscious and not just simulating various aspects of consciousness? The nature of consciousness makes it, by necessity, a wholly private affair (Koch, 2019; Libet, 2005). The only consciousness we can know with *certainty* is our own. Everything else is inference.

With the coming age of intelligent digital assistants, self-driving cars, and other robots serving us and increasingly guiding our lives, does it matter if these artificial intelligences (AIs) are actually conscious or just simulating consciousness?

More relevant for today's needs is the question: How can we make reasonable inferences about whether coma victims, or patients in vegetative or minimally conscious states, are conscious? Or whether these individuals are likely to recover? How can a family know whether it has enough information to take a patient off life support or whether the patient is likely to recover consciousness over time?

Also relevant for the world's growing numbers of vegetarians and vegans, can we now bring the tools of science to bear in assessing the level of pain suffered by animals by using a scientific framework? If a consensus based on scientific evidence develops in the coming years that animal agriculture and/or animal experimentation is indeed leading to significant pain and suffering in nonhuman animals, might such data affect cultural norms regarding such practices?

To answer these questions, can we create an informative "consciousness-ometer" (hereafter, *psychometer*)? We are using "consciousness" here to refer to the capacity for phenomenal/subjective experience. Whereas this inquiry has been relegated to philosophical musings until the past few years, we are now at a juncture where tools for measuring consciousness are starting to mature. This article examines the various tools and tests that search for the presence of and assess the complexity of consciousness as well as offering suggestions regarding how a psychometer could be created and refined over time.

Corresponding Author:
Tam Hunt, Department of Psychological and Brain Sciences, University of California, Santa Barbara
Email: tam.hunt@psych.ucsb.edu

Box 1. Glossary

Consciousness: the capacity for phenomenal/subjective experience

Measurable correlates of consciousness: any measurable correlate that can help in making reasonable inferences about the presence of conscious states within the object of study

Behavioral correlates of consciousness: behaviors that correlate with conscious states and may be used to reasonably infer the presence of consciousness

Neural correlates of consciousness: neural features and dynamics that are inferred to co-occur with or possibly cause conscious states

Creative correlates of consciousness: produced works, such as buildings, art, or artifacts of any sort, that may help in making reasonable inferences about the presence of consciousness

Oscillatory correlates of consciousness: a subset of neural correlates of consciousness that focuses on the correlation between oscillating electromagnetic fields produced by the brain and body and the dynamics of consciousness

Electromagnetic field correlates of consciousness: the oscillatory correlates of consciousness comprising electromagnetic fields

Theories of consciousness are abundant but are often untested or even untestable (Michel et al., 2019). Although a major coordinated testing program has yet to be conducted, in 2019, the Templeton World Charity Foundation embarked on a multiyear effort to examine several of the more prominent theories of consciousness in a series of one-on-one adversarial experimental tests, and the express intent was to distinguish among the various theories. The first head-to-head contest will feature global neuronal workspace (GNW) theory (Dehaene, 2014) and the integrated-information theory of consciousness (IIT; Oizumi et al., 2014).

Attempts to examine the presence or nature of consciousness in any particular circumstance, and related attempts to assess different theories of consciousness and their predictions, will face the problem of reasonable inference (abduction) because of a fundamental limitation on our individual and collective knowledge. Libet (2005) states the problem as follows: "Subjective experience cannot be directly measured by external objective devices or by external observations. Conscious subjective experience is accessible only to the individual having the experience" (p. 158) But this problem is surmounted frequently in practice, in that each of us reasonably infers that other humans are indeed conscious on the basis of their behavior and appearance. The same holds true for pets and many other animals. Making inferences about the presence of consciousness throughout the physical world relies on making similarly reasonable and incremental inferences, as discussed in this article. Inference is not certainty, but science does not demand certainty.

Koch (2019) offers a similar argument: "Because you are so similar to me, I abduce that you, too, have subjective, phenomenal states. The same logic applies to other people. Apart from the occasional solitary solipsist this is uncontroversial" (p. 155). We discuss Koch and Tononi's IIT further below.

In the present article, we propose a general framework for making reasonable inferences regarding the presence and type of consciousness that rests on various *measurable correlates of consciousness* (MCCs; see Box 1). MCCs (Hunt & Schooler, 2019) are any means for measuring different aspects of consciousness. In its current formulation, MCCs include as subcategories the well-known *neural correlates of consciousness* (NCCs) and the related, but broader, notion of *behavioral correlates of consciousness* (BCCs). It also includes the newly coined *creative correlates of consciousness* (CCC) category that is explained below. We discuss other potential subcategories below.

We also suggest that the various metaphysical positions with respect to the nature of consciousness may be, contrary to the commonly held view that such positions are outside the domain of science, empirically informed. With new tools and technologies at our disposal, these questions may become more than just philosophical.

The proposed framework is fundamentally Bayesian in its approach because it depends on each individual's prior judgments about the likelihood of some degree of phenomenal consciousness being present (or not) in the subject at issue. If individuals have significantly different priors, as they surely will, substantively

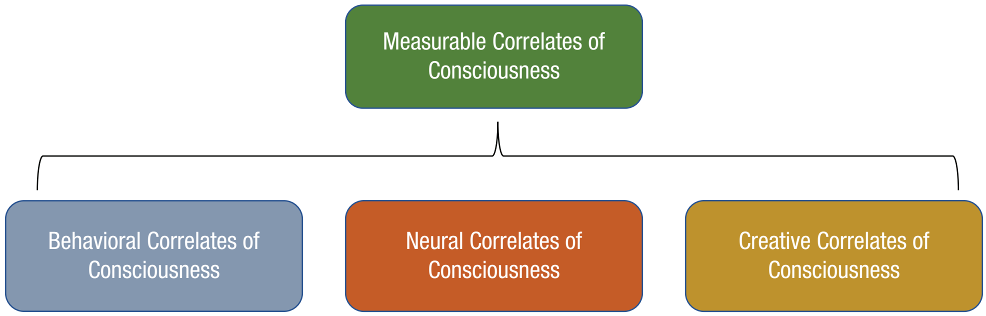

Fig. 1. The various types of measurable correlates of consciousness (MCCs).

different conclusions may be drawn from the same evidence. However, our approach may, over time, help to bridge the distance between different perspectives, even if this approach falls short of a definitive test or psychometer. The proposed framework is meant to provide a standardized and general set of tools for examining the universe of potential kinds of conscious entities and, through such examination, help to develop a community-based consensus about the presence and type of consciousness in various entities.

The MCCs

There is a small but growing field investigating how to assess the presence and complexity of consciousness in various entities. We can divide possible tests into three broad categories that collectively comprise the MCCs (Hunt & Schooler, 2019). We define the MCCs as all conceivable scientific measures for inferring the presence of consciousness. Let us look at each of these categories in turn.

Our present MCC taxonomy in Figure 1 is surely not exhaustive and others may wish to add their own categories. A likely fourth category would be *evolutionary correlates of consciousness*, meant to assess the degree of kinship between the organism and other organisms. For example, an invertebrate closely related to cephalopods, which are probably the most intelligent of invertebrates (and enjoy the highest capacity for consciousness among the invertebrates) might also be considered more likely to enjoy a richer type of consciousness. This inference is based, at least in part, on the evolutionary relatedness to creatures that are generally considered to experience more complex types of consciousness.

Another possible category would be the *oscillatory correlates of consciousness* (OCC) concept developed in Gallotto et al. (2017)—and also employed in Kumar et al. (2020)—"This review of oscillatory correlates of consciousness suggests that, for example, activity in the alpha-band (7–13 Hz) may index, or even causally support, conscious perception" (Gallotto et al., 2017, p. 1). This OCC category would be a subcategory of NCCs in our taxonomy in Figure 1.

We discuss below electromagnetic-field theories of consciousness and the likelihood that the primary seat of consciousness is the electromagnetic fields generated by the brain, giving rise to at least one scholar suggesting an *electromagnetic correlates of consciousness* category (Hales, 2017). This view of consciousness renders the OCCs/electromagnetic correlates of consciousness highly important, and we suggest below ways in which oscillations/resonance should be considered in developing a psychometer.

BCCs

Examining BCCs is an intuitive and historically common manner of assessing the presence and complexity of consciousness in both daily life and in clinical settings. There is no established methodology for using BCCs as a measure(s) of consciousness. Measures of NCCs and BCCs are complementary and, in general, should both be employed in any particular case.

At the most general level, we as humans assess the presence and complexity of consciousness present in other humans multiple times each day, consciously and unconsciously, through our conversations and other interactions with our fellow humans. Speech and other forms of direct communication are a form of BCCs that we use to assess the nature of others' consciousness. Each of us uses speech, both inwardly (introspectively) and externally with others, to convey our own thoughts and feelings too frequently to quantify. Most of us readily accept that other humans expressing thoughts and feelings through their own speech are, in fact, conscious in ways very similar to ourselves, on the basis of comparisons between others' speech and behavior and our own. Although this statement is not revelatory, it is important to state as a baseline approach for assessing the presence of consciousness in other beings.

In the AI context and attempts to simulate consciousness—independent of deeper questions about whether

AIs can ever be truly conscious rather than merely simulating consciousness—the well-known Turing Test (described as "the imitation game" by Turing himself; Turing, 1950) is meant to allow humans to judge the degree of thinking ability (what we would today describe generally as consciousness, given that the purpose of Turing's proposed test was to provide a practical means for determining if machines can think in a way that is largely similar to how humans think, or at least to be able to convincingly emulate thinking), if any, in an AI. The Turing Test was originally proposed to allow human participants to make a specific judgment based on responses from the test subject about the nature of the subject: Could it really think? Was it a human or a machine? The Turing Test is a way of using BCCs to inform opinions regarding the presence and type of consciousness in AIs. The human participant is asked to make a judgment about the nature of its conversation partner, based solely on these direct communications.

The BCC category encompasses far more than verbal forms of communication, however. BCCs can be used to inform opinions of the presence and nature of consciousness in a wide variety of nonverbal entities across the animal kingdom and further down the chain of complexity.

For example, cats cannot communicate their states of consciousness with words, and their neural architecture is quite different from that of humans. They have minimal prefrontal cortex, which is thought to be the center of many higher order activities of the human brain. But is a prefrontal cortex necessary for consciousness? Is language?

Cat behavior is complex and readily mappable onto human behavior in both overt and subtle ways. The fact that cats purr, flex their toes, and snuggle when petted in ways similar to how humans demonstrate pleasure while physically stimulated, vocalize loudly when hungry and stop vocalizing when fed, exhibit curiosity or fear about other cats or humans with various types of body language, and many other behaviors that we can easily observe if we have cats as pets, is fairly convincing evidence, for most of us, that cats are indeed conscious and have a rich emotional life.

Dennett (2008) argues that perhaps only dogs have consciousness of a type similar enough to humans such that their suffering is comparable with human suffering, and also that cats probably do not suffer in a way comparable with human suffering because they are not social animals in an evolutionary sense. Dennett's arguments may have been superseded by the recent substantial body of research that suggests that domestic cats are indeed social creatures that, for example, prefer human social interactions over food when given the choice (Vitale et al., 2019).

Considering young domestic cats (3–8 months old) and their attachment styles with their human owners, Vitale et al. (2019) found behavior and attachment styles similar in some ways to those observed in human infants. Using behavioral criteria established in the human infant literature, they concluded that cats display distinct attachment styles toward human caregivers: "Evidence that cats share social traits once attributed to dogs and humans alone would suggest that broader non-canine-specific mechanisms may be needed to explain cross-species attachment and socio-cognitive abilities" (Vitale et al., 2019, p. R864).

LeDoux's (2019) book, *The Deep History of Ourselves*, detailing the development of consciousness through the long history of our planet, takes a more behaviorist view and argues for a conservative approach to BCCs. He contends, similarly to Dennett (2008), that the default position for making any determinations about the presence of consciousness should be, if possible, to explain behaviors without inferring a role for consciousness.

We advocate a less conservative view, which is part of the recent progressive trend toward treating the study of animal minds the same way—or in similar ways—that we do human minds, on the basis of a Bayesian prior informed by the strong evolutionary and genetic commonalities between humans and other mammals. There is a strong kinship and numerous behavioral similarities between humans and other animals, along with the well-established fact that biological change occurs slowly and incrementally, even in the "punctuated equilibrium" modification to Darwin's natural selection, abhorring "jumps": *Natura non facit saltus* (Darwin, 1859/2014; Koch, 2019).

Griffin has examined the nature of animal minds in various works since the 1970s, including his 2001 book, *Animal Minds: Beyond Cognition to Consciousness*, in which he states: "In a sharp break with the traditional conviction that the mental experiences of animals cannot be studied scientifically, some of us have begun to try" (Griffin, 2001, p. xiii). There is now a relatively long history of examining the nature of consciousness in animals, and the 20th-century "controversy" over discussions of animal or even human minds, and the soft taboo about studying the mind directly, has rightly receded into the distance.

Throughout his extensive body of work, Panksepp showed that there are substantial commonalities across species, including among mammals, other vertebrates, and even invertebrates, in terms of seven highly conserved emotional circuits: "Panksepp carved out seven primary emotional systems called SEEKING, CARE, PLAY, and LUST on the positive side, whereas FEAR, SADNESS, and ANGER belong to the negative affects." (Davis & Montag, 2019, para. 1; Panksepp & Biven, 2012). It is important to note that these words represent the names of these neurological circuits rather than the emotions themselves. This physiological and evolutionary evidence across diverse species demonstrates the common emotional/consciousness biological heritage that perhaps all complex animals share. Panksepp suggested, however, that some of these seven circuits may have emerged in more complex animals.

There is no framework at this juncture for quantifying BCCs similarities sufficient to make a judgment about the presence and complexity of consciousness on the basis of BCCs alone. We suggest, on the basis of this broad overview, that BCCs should be the start of an intuitive and Bayesian approach to an analysis of the presence and complexity of consciousness in any given life form. The NCCs, CCCs, and other MCCs will then allow the community of scientists to gather additional data, some of which can be quantified more specifically, to make the most informed judgments about the presence and complexity of consciousness. This is necessarily an iterative and community-based process.

NCCs and "signatures of consciousness"

The NCCs have received the most scientific attention as a means for assessing the presence and complexity of consciousness. The term was first coined by Crick and Koch (1990) as part of their quest to determine what parts of the brain are necessary and sufficient for conscious experience. The NCCs have been defined as the minimal neuronal mechanisms jointly sufficient for any one specific conscious percept (Crick & Koch, 1990; Koch, 2004, 2019).

Researchers have developed tests for cognition and consciousness in coma patients and vegetative patients (e.g., Casarotto et al., 2016; Dehaene, 2014; Kouider et al., 2013). For example, when inferring whether a vegetative patient is conscious in any way, because there are neither observable behaviors (BCCs) nor creative products (CCCs), we must examine only NCCs through various neuroimaging tools such as electroencephalography (EEG), magnetoencephalography (MEG), functional MRI, and transcranial magnetic stimulation (TMS).

Numerous theories of consciousness have been proposed in recent decades. In exploring the MCC categories, we focus primarily on two of the more prominent theories of consciousness at this time: Dehaene's GNW theory and Tononi's IIT.

First developed as a computational model by Baars (1993), GNW theory offers a promising neural framework to assess NCCs (Dehaene & Changeux, 2005; Dehaene & Naccache, 2001; Dehaene et al., 1998, 2003, 2006). In brief, GNW specifies that a state is conscious when it (or its contents) is present in the GNW, making the contents of that state globally *accessible* to multiple systems, including long-term memory, motor, evaluative, attentional, and perceptual systems (Dehaene et al., 1998, 2006; Dehaene & Naccache, 2001). Dehaene and colleagues assert that a kind of phase transition occurs from preconscious states to consciousness: GNW predicts that consciousness is a nonlinear function of stimulus salience in which a gradual increase in stimulus strength should result in a sudden transition of the neuronal workspace into a corresponding activity pattern. (Dehaene et al., 2003).

Though it has arguably experienced several rounds of refinement over the years, at its core, GNW theory suggests four "signatures of consciousness" that extend the notion of NCCs to specific aspects of brain activity that it suggests are necessary for conscious awareness, rather than being only correlated with consciousness (Dehaene, 2014). The signatures are, in brief, as follows: (a) a sudden ignition of parietal and prefrontal circuits, (b) a late slow event-related potential (ERP) wave called the P300, (c) a late and sudden burst of high-frequency oscillations, and (d) long-range synchronization of neural firing across distant brain regions (Dehaene, 2014).

ERP approaches have a lengthy history, and much attention has been devoted to both visual and auditory processing. Time-locked to sensory, motor, or cognitive events, ERPs provide a safe and noninvasive approach to study NCCs and reflect the summed activity of postsynaptic potentials produced when a large number of similarly oriented cortical pyramidal neurons fire in synchrony while processing information (Peterson et al., 1995). ERPs are classically divided into two categories, exogenous and endogenous, and both are relevant to NCC research. Exogenous ERPs—early waves peaking within approximately 100 ms after a stimulus—reflect preattentive "sensory" processing that depends largely on the environment and reflect passive preconscious activity. Conversely, endogenous ERPs reflect information processing and attention allocation.

Many researchers, including Dehaene, have focused on the P300 ERP as an especially promising candidate for NCC research. The P300 (also more informally referred to as the P3) is defined as a positive peak of electrical scalp activity starting approximately 300 ms after the onset of a stimulus. The P3 can be parsed even further into P3a, which reflects stimulus-driven frontal attention mechanisms during task processing, and P3b, which originates from temporal-parietal activity associated with attention and appears related to subsequent memory processing. The P3 is modality independent and is produced regardless of stimulus type (e.g., auditory or visual), and no overt action on the part of the subject is required to elicit P3 activity (Falkenstein et al., 2002). Dehaene (2014) suggests that in cortical areas in which stimuli do not result in a P3, such activity does not reach the level of consciousness, an idea based on self-reports correlated to observed EEG signals.

Examining a similar set of signatures, Kouider et al. (2013; Dehaene was a coauthor) assessed the neural markers of perceptual consciousness in 5- to 12-month-old human infants. Results demonstrated the same two-part response (a slow onset response ~200–300 ms after stimulus followed by a rapid "essentially all or none change in brain activity" transition from ~300 ms) to visual masking as seen in adults who can verbally report their experience (Kouider et al., 2013, p. 377).

Although earlier work in vegetative and minimally conscious patients has shown the presence of a P3 to be an index for those who are most likely to regain more normal states of consciousness (Sitt et al., 2014), more recent research has painted a slightly different picture, which brings to light the degree to which research on the NCCs is still very much in flux. For example, several studies have found that many patients in a vegetative state produce a P3b (Faugeras, 2011; Fischer et al., 2010; Höller et al., 2011; King et al., 2013; Sitt et al., 2014; Tzovara et al., 2015). Moreover, in studies that employed a manipulation of awareness and task relevance in a backward-masking task, the P3b was present in some of the unaware, task-relevant conditions and was absent in some of the aware, task-irrelevant conditions (Pitts et al., 2012; Pitts, Metzler, & Hillyard, 2014; Pitts, Padwal, et al., 2014).

Authors noted that these findings were somewhat contradictory to other studies to date, in that relatively few studies have found a P3b without conscious perception. However, these findings further support the growing body of research that focuses on attentional modulation in the absence of awareness (Aru & Bachmann, 2013; Bernat et al., 2001; Koch & Tsuchiya, 2007; Tallon-Baudry, 2012; Tsuchiya & Koch, 2009; Wyart & Tallon-Baudry, 2008). Note that in a recent review article, Dehaene addressed this debate: "It remains unclear whether P3b is correlated with awareness . . ., post-perceptual processes . . ., or both" (Mashour et al., 2020, p. 780).

Other ERPs have been proposed as candidates for NCC research for over 3 decades, including the P1 component (Pins & Ffytche, 2003), mismatch negativity (Schlossmacher et al., 2020), and the midlatency visual awareness negativity (VAN; Koivisto & Revonsuo, 2010; Pitts et al., 2012; Railo et al., 2011). Having received substantial support as an ERP candidate related to conscious perception, the VAN is an ERP deflection that appears around 100 ms after the stimulus onset and peaks around 200 to 250 ms; it is localized to the posterior cortex. An extensive recent review of the literature concluded that the VAN reflects the earliest and most consistent signature of visual phenomenal consciousness (Förster et al., 2020). One important consideration that has been common in NCC research is the notion that brain activity related to perceptual processing and awareness can be and often is misattributed to the neural activity related to reporting of such awareness (Pitts, Metzler, & Hillyard, 2014; Pitts, Padwal, et al., 2014; Tsuchiya et al., 2015). For studies of visual awareness, an approach to help discriminate this underlying confound has been to employ masking-based tasks, such as inattentional blindness and backward masking in concert with task manipulations (Shafto & Pitts, 2015). Specific to delayed-report or no-report paradigms that incorporate visual tasks, several studies have reported that the VAN (but not the P3b) indexed awareness (Pitts et al., 2012; Schelonka et al., 2017; Schlossmacher et al., 2020; Shafto & Pitts, 2015).

We next examine a different but related approach to the NCCs. Adopting a richly quantitative approach, Casarotto et al. (2016) measures a perturbational complexity index (PCI) as a simpler proxy for consciousness, conceived as integrated information. Tononi coauthored the Casarotto et al. article, and Tononi's IIT is widely considered to be one of the more popular extant theories of consciousness. IIT suggests that integrated information is consciousness, though in its most recent formulation (Version 3.0), the theory is modified such that consciousness is instead considered to be identical to the maximally integrated cause–effect repertoire (MICE; Koch, 2019; Oizumi et al., 2014).

Tononi and colleagues acknowledge that measuring MICE or integrated information (Φ) in any biologically complex context is extremely difficult because it requires measuring all information flows in all channels. The PCI was developed as a more tractable means for measuring mammalian brain activity and relies on quantification of electrical activity with sophisticated EEG during TMS of the brain. PCI is a measure of the elasticity of neurons and neuron complexes under perturbation by TMS. It is thought that the less elastic a neuron, the more it is firing and thus contributing further to consciousness.

Through this measurement of elasticity, the PCI measures interconnectedness between different parts of the brain and activity within those information pathways: "PCI directly gauges the ability of many functionally specialized modules of the thalamocortical system (differentiation) to interact rapidly and effectively (integration), thus producing complex patterns of activity" (Casarotto et al., 2016, p. 719).

PCI has also been able to predict with reasonable accuracy the recovery of some patients in a vegetative state (Casarotto et al., 2016; Koch, 2019). Casarotto et al.

(2016) stated: "PCI offers a reliable, independently validated stratification of unresponsive patients that has important physiopathological and therapeutic implications. In particular, the high-PCI subgroup of VS [vegetative state] patients may retain a capacity for consciousness that is not expressed in behavior" (p. 718). In other words, the researchers found that some vegetative patients were likely to have significant capacity for conscious states despite their lack of observable behavior or other apparent signs of awareness.

Several researchers, including Koch (2019), Tononi et al. (2106), and Boly and Massimini (Massimini et al., 2009), view the PCI measure as an effective but far-from-perfect psychometer, even in its current state. Koch elaborates on his views on PCI in his 2019 book, *The Feeling of Life Itself* (Koch, 2019):

> While the PCI index is motivated by IIT, it crudely estimates differentiation and integration. . . . A true phi-meter [psychometer] should reflect the waxing and waning of experience during wakefulness and sleep, how consciousness increases in children and teenagers until it reaches its zenith in mature adults with a highly developed sense of self, with, perhaps, an absolute maximum in long-term meditators, before it begins its inevitable decline with age. Such a device would generalize across species, whether or not they have a cortex, or, indeed, any sort of sophisticated nervous system. For now, we are far from such a tool. In the interim, let us celebrate this milestone in the millennia-old mind-body problem. (p. 104)

The PCI and MICE techniques arguably represent a high-water mark for current efforts to measure complex consciousness, and yet the PCI remains a relatively crude scalar measure that does not correspond specifically to IIT.

A more recent and perhaps superior method, however, developed in Leung et al. (2021), calculates "integrated information structures" in fruit-fly brains. The researchers concluded that their new measure of mechanism-level (as opposed to global-level) Φ was a better tool than the simpler scalar system-level Φ value, which is the key diagnostic tool of IIT, because the new measure provides more than a scalar value to compare the capacity for consciousness.

It is indeed the case that Φ is a scalar value, as is Ω, the analogous scalar value in GRT (Hunt, 2011, 2020). However, IIT also includes "qualia constellation" tools for characterizing the nature of consciousness as specific shapes in an abstract information space with far more information than a simple scalar value. Moreover, as Leung et al. (2021) themselves note, the methods used to measure integrated information structures do not strictly follow IIT's protocols. Nevertheless, this article seems to represent significant progress in operationalizing complex measures of consciousness in biological entities.

Tests developed in the context of fruit flies have limited value in the human context, and in the broader context of questions about phenomenal consciousness, until they are validated more widely. However, combining BCC measures in fruit flies and other insects and simpler animals with NCC measures such as integrated information structures, is a good example of how the MCC framework we have offered in this article may be used to develop community-based consensus about consciousness and its capacity in creatures as distant evolutionarily from ourselves as fruit flies.

The approach taken by Leung et al. (2021), however, may miss key features of information integration because it does not measure global EEG fields and their interactions, such as cross-frequency coupling or harmonic coupling (a specialized case of maximal cross-frequency coupling), focusing instead only on local field potential and its more localized electromagnetic field dynamics. We discuss below some of the evidence suggesting that the brain's local and global electromagnetic fields may be the primary seat of consciousness. Under this approach, then, we would look to these field dynamics for our primary NCC and "signatures of consciousness."

CCCs

Creative output is another source of data for assessing the presence of consciousness. If, for whatever reason, we cannot examine neural or behavioral correlates of consciousness, we may be able to examine CCCs for clues. In addition, in any circumstance in which the presence of consciousness is in doubt, it will be beneficial to use as many tests of consciousness as are available, including separate tests focused on NCCs, BCCs, and CCCs.

For example, when we examine ancient architectural structures such as Stonehenge or other megalithic structures, or cave paintings in Europe that have been determined to be as much as 65,000 years old, are we reasonable in judging the creators of these items to be conscious in ways similar to our own? We cannot see the creative process or know with any certainty what creatures created these works of art. In other words, we have no way of examining BCCs or NCCs because the creators are not present and not accessible. Despite this lack of information, however, most of us would answer in the affirmative: The creators of these works were very likely conscious in ways quite similar to how we are conscious. We know from experience that it would take high intelligence and consciousness to produce such works today, so most of us would reasonably infer that our ancient ancestors had levels of consciousness similar to those of humans today.

What if we eventually find nonhuman artifacts on Mars or other bodies in our solar system? Can we reasonably infer that whatever entities created such artifacts were conscious? It will depend on the artifacts in question, but if we were to find items or dwellings similar to what we would find on Earth but that were clearly not human in origin, most of us would reasonably infer that the creators of these artifacts were also conscious in certain ways similar to humans' consciousness. The degree of similarity would not be ascertainable without more information, but the presence and relative complexity of consciousness in such creators would, it seems, be a reasonable inference for the majority of scientists asked to make such an inference.

Closer to home, AI has produced increasingly impressive art, and one piece fetched more than over $400,000 at a 2018 art auction (Saltz, 2018). At what point do reasonable persons conclude that sophisticated art creation suggests the presence of some kind of consciousness? To answer this question empirically, we could conduct a kind of "artistic Turing Test" and ask study participants to consider various works of art and say which ones they conclude must have been created by a human. And if AI artwork consistently fools individuals into thinking it was made by a human, is that good evidence to conclude that the AI is at least in some ways conscious? We are not suggesting an answer to this question, but it seems unlikely that many scientists, if asked to judge whether the creator of an artwork that fooled a majority of people judging the artwork, would, given this level of artistic achievement, conclude that the AI was thus conscious in some manner. This has always been the difficulty with the Turing Test itself: Even if machines can fool human observers about certain aspects of human behavior and consciousness, this evidence, by itself, would not lead to any necessary conclusions about the machine being actually conscious.

These types of creative output may also shed light on the degree to which self-consciousness may be present in the creator(s). In our view, self-awareness is not necessary for the phenomenal consciousness that is the focus of the MCC framework or of GRT. Rather, we view self-consciousness as a more refined type of consciousness that arises only when sufficient complexity allows for a model of the organism itself in the world model created by the brain (this is the "me" in the distinction between "me" and "I" that James first noted in his seminal work *Principles of Psychology* [James, 1890]). Awareness of this model of self in the larger world model is what we call self-awareness or self-consciousness. Examining the manner in which the works in question relate to the creator herself—again only through various kinds of reasonable inference and without any certainties—we may draw some provisional conclusions about the possible level of self-consciousness in the creator(s).

We may ask similar questions about the presence of consciousness in creatures that probably do not have a sense of self-consciousness, such as the creators of termite mounds or ant colonies, or bowers created by bower birds or fish. Are these structures, if we consider them separately from their creators, helpful data for inferring the presence of consciousness in their creators? And what if these kinds of structures change over time on the basis of different generations, or change on the basis of location, suggesting that it is not simple instinct leading to construction of these complex structures? Such data can be informative even if it will be interpreted differently by each observer on the basis of their particular Bayesian priors.

We reserve judgment on these specific questions for now, but as a general observation, we agree with Koch (2019), who argued in *The Feeling of Life Itself* that any AI instantiated in a von Neumann "feedforward" type of computer, which has no (or very limited) feedback processes from higher-levels of abstraction back to lower-levels of abstraction, which are prevalent in brains and often labeled "reentrant" or "recurrent" processing, is highly unlikely to enjoy any complex consciousness, even if such an AI is otherwise impressive in its achievements and in its ability to simulate aspects of complex consciousness.

A computer built on resonance principles—a "neuromimetic" computer (Colin Hales, personal communication, November 22, 2020)—that produces the same kinds of EM fields as the brain and body could theoretically be conscious as opposed to simulating consciousness in certain key aspects. This is the topic of our next section.

How Do We Develop an Informative Psychometer?

While there is not yet a widely accepted or reliable psychometer—and there perhaps never will be a single device or tool that reliably measures the capacity for consciousness in all circumstances—various researchers have suggested ideas, including Dehaene, Changeux, Tononi, Koch, Casarotto, Leung, Tsuchiya, and others. We suggest further ideas here, relating to various types of synchronization and resonance chains, such as harmonic oscillations in neural electromagnetic fields.

Demertzi admonishes when assessing the presence of consciousness: "Finding reliable markers indicating the presence or absence of consciousness represents an outstanding open problem for science" (Demertzi et al., 2019, p. 1). Demertzi and colleagues, and various other researchers, have been working to identify reliable markers, but this is still, as we have seen, a nascent field.

Dehaene (2014) states the problem clearly, in focusing on NCCs: "Could any brain image ever prove or disprove the existence of a mind?" (p. 211). Dehaene answers this question in the affirmative, however. He not only has various discussions about the NCCs and signatures of consciousness (what he defines as the necessary and sufficient correlates of consciousness), but also he recognizes that "no single test will ever prove, once and for all, whether consciousness is present" (p. 214). He, instead, recommends a battery of tests be developed to bolster confidence about the presence of consciousness in various contexts. His work is focused on human subjects, but he also discusses animal consciousness in his 2014 book.

Tononi and Koch, as discussed above, focus on measuring MICE and "integrated information" as a proxy for measuring the capacity for consciousness. In brief, this theory suggests that anything that integrates at least one bit of information has at least a minimal amount of consciousness. A light diode, for example, contains one bit of information and thus has the most rudimentary type of consciousness. With just two possible states, on or off, however, it is a rather uninteresting kind of consciousness.

Koch, accepting and defending IIT as the best working theory of consciousness, raises the possibility of panpsychism expressly, worth quoting at length (Koch, 2019):

> To the extent that I'm discussing the mental with respect to single-cell organisms let alone atoms, I have entered the realm of pure speculation, something I have been trained all my life as a scientist to avoid. Yet three considerations prompt me to cast caution to the wind.
>
> First, these ideas are straightforward extensions of IIT—constructed to explain human-level consciousness—to vastly different aspects of physical reality. This is one of the hallmarks of a powerful scientific theory—predicting phenomena by extrapolating to conditions far from the theory's original remit. There are many precedents—that the passage of time depends on how fast you travel, that spacetime can break down at singularities known as black holes, that people, butterflies, vegetables, and the bacteria in your gut use the same mechanism to store and copy their genetic information, and so on.
>
> Second, I admire the elegance and beauty of this prediction. The mental does not appear abruptly out of the physical. As Leibniz expressed it, *natura non facit saltus*, or nature does not make sudden leaps (Leibniz was, after all, the co-inventor of infinitesimal calculus). The absence of discontinuities is also a bedrock element of Darwinian thought.
>
> Intrinsic causal power does away with the challenge of how mind emerges from matter. IIT stipulates that it is there all along. (p. 160)

In our own work on general resonance theory (GRT; Hunt, 2011, 2014, 2016, 2019, 2020; Hunt & Schooler, 2019; Schooler et al., 2011), we share this "panpsychist" foundation with IIT and other panpsychist theories of consciousness. Indeed, Koch wrote the foreword to Hunt (2014), a collection of essays examining the possibilities and consequences of panpsychism in various fields. We accept as a working hypothesis that any physical system has some associated consciousness, however rudimentary it may be in the vast majority of cases.

Rather than integrated information or MICE as the key measure of consciousness (as in IIT), GRT focuses on the degree to which parts of a whole resonate at the same or similar frequencies. These parts, in any complex consciousness such as exists in animals, exist in a nested hierarchy of faster frequencies at more fundamental levels in the hierarchy to slower frequencies at the top. The phase transitions in information transfer made possible through such shared resonance is the key mechanism that allows for the unity of consciousness in each moment (Hunt & Schooler, 2019).

In the case of the human and mammalian consciousness, more generally, resonance indicates shared electric field oscillation rates, such as theta, alpha and gamma band synchrony as key aspects of the mammalian "resonome." Local and global electromagnetic fields allow for rapid transfer of information at the local and global level. It is these information flows across different parts of the brain that create a particularly complex kind of phenomenal consciousness. These dynamics lead to the working hypothesis in GRT that the dynamics of the brain's EM fields are identical to the dynamics of consciousness (Hunt, 2020; Hunt & Schooler, 2019).

Synchronization, the ability of oscillators to mutually adapt their rhythms (oscillation cycles), is a ubiquitous natural phenomenon (Pikovsky et al., 2002; Winfree, 1980). For example, neural synchronization in the gamma range has been thought to be a strong candidate for an NCC since at least the early 1990s. We now know that gamma synchrony is not solely, or even primarily, responsible for human or mammalian consciousness, but it is clearly an integral component. Gamma synchrony has been reported both in subcortical structures (Akam & Kullmann, 2012; Steriade et al., 1993; Zhou et al., 2016) and in cortical areas (Fries, 2015; Gray & Singer, 1989; Gregoriou et al., 2009). Gamma rhythms emerge in activated neural circuits, in which fast-spiking inhibitory neurons play a central role (Cardin et al., 2009; Tiesinga & Sejnowski, 2009; Traub et al., 1996). A prime example is the emergence of gamma rhythms in the early visual cortex during visual stimulus processing (Brunet et al., 2013; Gail et al., 2000; Gray & Singer, 1989; Hermes et al., 2015; Ray et al., 2013; Roberts et al., 2013).

More recent research has found that theta rhythms are likely the most common rhythm in human brain waking states and, because they are the slowest non-sleeping brain rhythm, seem to act as an oscillatory scaffolding or backbone for other faster rhythms to persist and travel through the brain (Groppe et al., 2013; Klimesch, 2018; P. Lakatos et al., 2005).

A psychometer developed pursuant to GRT would, insofar as it focuses on neural correlates of consciousness, evaluate the degree of shared resonance or synchronization of various types among the regions of the brain, other organs, and peripheral nervous system (Hunt, 2019, 2020; Hunt & Schooler, 2019; Young et al., 2019), and resulting information/energy[1] flows through these various parts, as the measure of consciousness. This analysis entails multiple spatial and temporal scales because there are multiple scales of synchronized fields.

Various synchrony indexes have been developed that measure the degree of electromagnetic field oscillatory synchrony between parts of the brain and, depending on how these indexes are employed, may serve as a proxy for the capacity for phenomenal consciousness and/or connectivity in the brain (for an overview of various synchrony indexes, see Ghanbari & Moradi, 2020).

Humans and other mammals enjoy a particularly rich kind of consciousness, because there are many hierarchical levels of pervasive shared synchronization throughout the brain, nervous system, and body (Hunt & Schooler, 2019; Klimesch, 2018; P. Lakatos et al., 2005; Walleczek, 2006). By analyzing the complex nested resonant hierarchy within neural structures, GRT's approach has much in common with Dehaene's GNW and its focus on various types of brain waves and endogenous electrical potentials, such as long-range synchronization and the P3 ERP wave (Dehaene, 2014; Dehaene & Naccache, 2001).

Key differences, however, between GRT and GNW exist and are described in detail in Hunt & Schooler (2019). The primary difference is that whereas GNW focuses only on the highest-level shared resonance, as exemplified by long-range electric field synchronization and the P3 wave, GRT would include in its analysis as much of the specific nested resonant hierarchy as it is reasonably feasible to measure with available tools, such as the synchrony indexes mentioned above, as well as tools developed specific to GRT (Hunt, 2020).

How to Apply the MCC Framework to Measure Consciousness

The logical chain of the MCC framework is straightforward and may be summarized as follows, starting necessarily from a first-person perspective: "I know I'm conscious; I assume other humans are conscious because they act in various ways like me and do many intelligent things; I engage in similar reasonable inferences when assessing whether various animals are conscious and to what degree; we can use the same process of reasonable inference in probing the presence of consciousness all the way down the chain of physical complexity." Figure 2 summarizes this approach.

In the MCC framework more generally, we propose an iterative "weight of the evidence" approach (i.e., the Bayesian approach discussed above) for examining the presence and nature of consciousness in any particular object of study. Under this approach, we would in any particular case pose a number of "questions," in all areas of the MCCs as described above, to the object of study, and it would answer in whatever ways it can. "Questions" can be verbal in nature, or physical probes, or any kind of interaction between the tester and the object of study.

On the basis of whatever responses are received, we then make the same kinds of reasonable inferences about the presence and nature of consciousness that we do every day, implicitly, when it comes to other humans or animals. This question-and-answer process is meant to be truly general and may apply to any candidate for consciousness, whether it is a human, animal, plant, bacterium, AI, or any physical object.

Additional Thoughts on Electromagnetic Field Theories of Consciousness

One possibility that arises within GRT and some other field theories of consciousness is that consciousness resides primarily within the various electromagnetic fields generated by matter (John, 2001; Jones, 2013; McFadden, 2002a, 2002b, 2013; Pockett, 2000, 2012). In animals, and particularly mammals with complex brains, such fields are the most pronounced and most complex, resulting in a concomitantly rich consciousness. It is

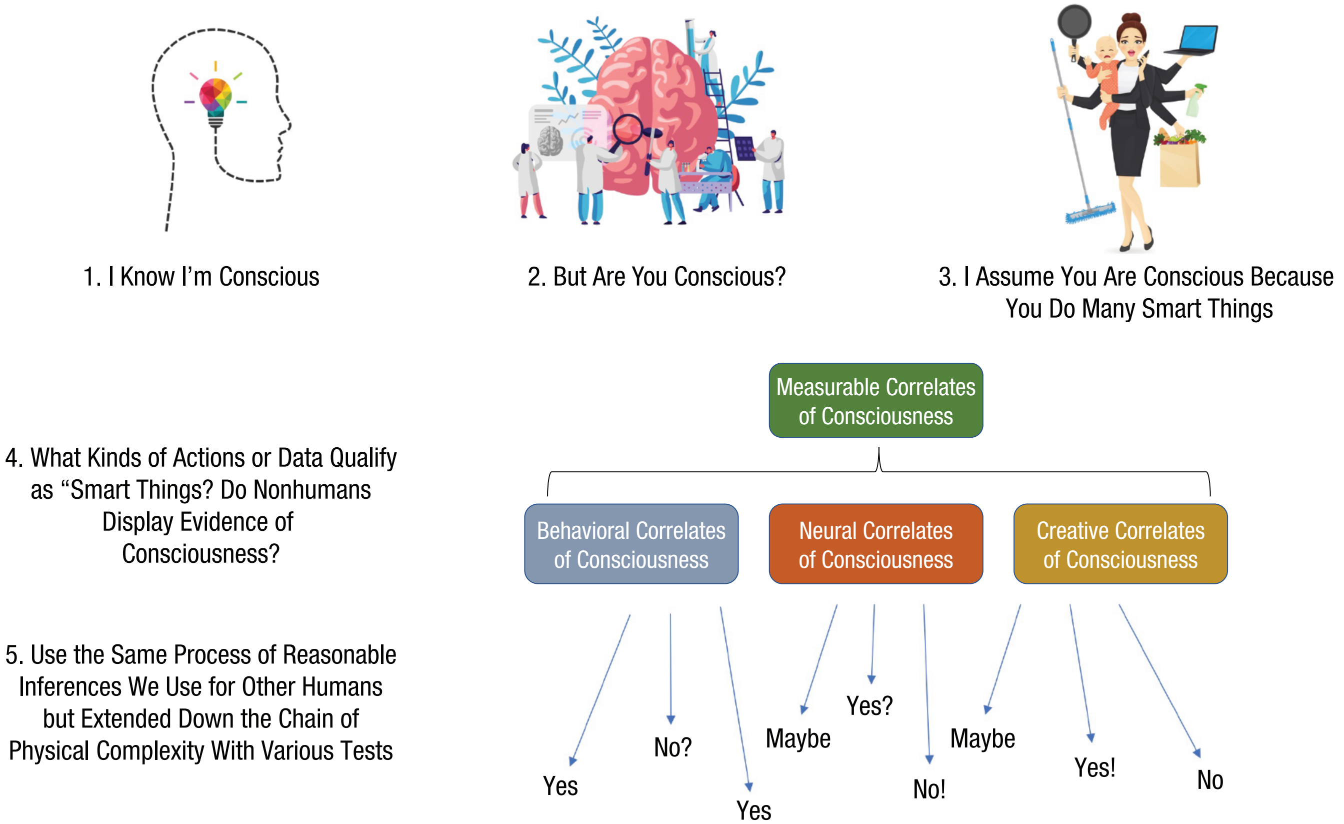

Fig. 2. Summary of the suggested approach for assessing the presence and nature of consciousness in any physical structures. The "yes," "no," "maybe" responses listed in Step 5 refer to the conclusions the reasonable observer will draw, after asking the various kinds of questions prompted by the measurable correlates of consciousness (MCC) categories, with respect to the likely presence of some kind of consciousness necessary to explain the observed data.

not necessarily the case that all such fields have any degree of consciousness.

EEG, MEG, electrocorticography (ECoG) and other electrical- or magnetic-field-measuring devices measure these fields produced by the brain and the body (e.g., electrogastrograms and electrocardiograms are for gastric neurons and cardiac neurons, respectively). There is a long tradition of EEG and MEG measurements but little consensus over what exactly these devices are measuring (Cohen, 2017). A number of scholars have suggested that these fields are not epiphenomena or indirect products of the mechanisms of consciousness, but may, instead, be the primary seat of consciousness (Hales, 2017; Klimesch, 2018; P. Lakatos et al., 2019). Thus, measuring these fields constitutes direct measurements of consciousness, but objectively rather than subjectively.

As one example, recent research shows that induced oscillations using intermittent theta-burst stimulation (iTBS) can be highly effective in treating depression (Cole et al., 2020); 90% of patients resistant to traditional treatments display significant improvement after treatment with iTBS. That such entrainment of oscillating electrical fields in the brain seems to have a remarkable impact on mood and long-term function is support for electromagnetic field theories of mind. This is the case because use of exogenous EM fields to influence endogenous EM fields, thereby achieving measurable changes in consciousness, demonstrates the causal efficacy of these fields.

We are only starting to learn what the various frequencies and patterns of electrical and magnetic activity mean in terms of conscious experience. Some scholars are starting to sketch the details of a common "resonome" that describes the taxonomy and landscape of observed oscillations (e.g., Klimesch, 2018; P. Lakatos et al., 2019; Lea-Carnall et al., 2016).

If consciousness is primarily associated with electromagnetic fields, more specific and perhaps more simple testing paradigms become possible that will not require tracking, for example, all integrated information within a given animal brain. We would, instead, measure the oscillating fields and their interactions.

If we accept the hypothesis that EEG and MEG may be measuring direct mechanisms of consciousness (rather than epiphenomena), we may then use existing tools and techniques to quantify and characterize the

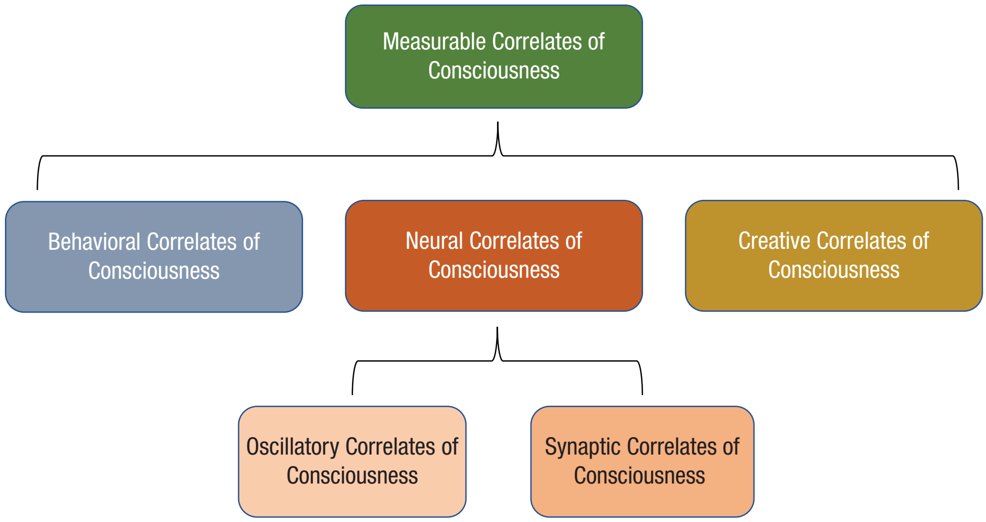

Fig. 3. Oscillatory correlates of consciousness plus synaptic correlates of consciousness may jointly constitute the neural correlates of consciousness.

various types of brain waves, and harmonic and nonharmonic relationships present within brain waves, as a way to measure resonance and thus consciousness directly. This approach reduces the need to collect data on the trillions of synaptic interconnections between neurons, or to ponder what other types of connections may be present and meaningful. Instead, such an approach may make measurement of even complex mammalian consciousness tractable using existing tools and techniques such as the various types of synchrony indexes discussed briefly above.

In sum, if indeed electromagnetic fields are the primary seat of consciousness, when we look at an EEG or MEG data chart, we are looking directly, in a manner of speaking, at the real-time dynamics of consciousness—or at least the highest-level manifestation thereof, the top of the nested hierarchy of electromagnetic fields that may constitute the mechanisms of consciousness.

This framing leads to an additional refinement of the MCCs to include OCCs and *synaptic correlates of consciousness* as two subcategories of the NCCs, as shown in Figure 3. These jointly constitute the NCCs. They are a gestalt, but it may be the case that measuring the OCCs is a more achievable task, perhaps significantly more so, than measuring the SCCs, because of the availability of various synchrony indexes for measuring cortical EEG rhythms with increasing resolution and specificity.

Reflections on Testing the Philosophical Foundations of Theories of Consciousness

It is generally assumed that broad metaphysical assumptions about the nature of consciousness are untestable and thus rendered forever "merely" philosophical and not scientific. The techniques outlined in this article suggest that we may now have a number of tools available that provide a path of reasonable inference for informing judgments about metaphysical foundations in the same manner as we would employ for specific cases.

For example, if the community of scholars is able to establish some degree of consensus about appropriate tests of consciousness, covering all types of MCCs, we may then, over the span of time, use these tests to assess the presence of consciousness throughout the scale of nature, including in simpler animals, and potentially protists, bacteria, and even plants. We might go further still and consider objects that are not generally considered to be alive or conscious—without making any a priori judgments about whether such entities should be considered to enjoy any type of consciousness. As mentioned above, this is what is meant by describing the proposed framework as a "general" framework in that it allows us to pose relevant questions and obtain data that may then inform discussions about the presence of consciousness throughout nature.

For example, examining the presence of rudimentary consciousness in even relatively simple forms of matter—an area of active debate with respect to what is known as panpsychism (Chalmers, 1996; Goff, 2017; Griffen, 1997), we may consider some particle physics experiments to constitute an existing category of observation, in terms of probing the behavior of even single particles or ensembles of particles, under various conditions. Freeman Dyson, a physicist, intriguingly stated in his 1979 book *Disturbing the Universe* that "the processes of human consciousness differ only in degree but not in kind from the processes of choice between quantum states which we call 'chance' when made by electrons" (Dyson, 1979, p. 249). David Bohm, another American physicist, wrote similarly that "even the electron is informed with a certain level of mind" (Hiley & Peat, 1987, p. 443; see also Bohm, 1990).

The proposed MCC framework is a general testing framework that can transform what have been considered only philosophical questions into scientifically informative ones. Under the proposed approach, broad philosophical frameworks about the nature of mind and its relation to matter, such as emergentist materialism or panpsychism, can also be investigated.

With data in hand, these broad questions may now be informed by science rather than remaining exclusively philosophical inquiries. Even with such data in hand, however, the degree to which consciousness manifests in the universe will surely remain a vibrant debate for decades to come.

Transparency

Action Editor: Laura A. King
Editor: Laura A. King
Declaration of Conflicting Interests
The author(s) declared that there were no conflicts of interest with respect to the authorship or the publication of this article.

Note

1. Information is generally defined as a subjective aspect of the physical world, whereas energy is an objective aspect; but in this context we are using these terms interchangeably because we define information as aspects of energy that we can measure. Thus, all physical dynamics consist of nothing more than energy flows, but those energy flows that we can measure may be labeled "information" and quantified using established information theoretic concepts. We will, however, generally refer to "information/energy flows" simply as "information flows" from now on in this article, for simplicity's sake.

References

Akam, T., & Kullmann, D. M. (2012). Efficient 'communication through coherence' requires oscillations structured to minimize interference between signals. *PLOS Computational Biology*, *8*(11), Article e1002760. https://doi.org/10.1371/journal.pcbi.1002760

Aru, J., & Bachmann, T. (2013). Phenomenal awareness can emerge without attention. *Frontiers in Human Neuroscience*, *7*, Article 891. https://doi.org/10.3389/fnhum.2013.00891

Baars, B. J. (1993). *A cognitive theory of consciousness*. Cambridge University Press.

Bernat, E., Shevrin, H., & Snodgrass, M. (2001). Subliminal visual oddball stimuli evoke a P300 component. *Clinical Neurophysiology*, *112*(1), 159–171. https://doi.org/10.1016/S1388-2457(00)00445-4

Bohm, D. (1990). A new theory of the relationship of mind and matter. *Philosophical Psychology*, *3*(2–3), 271–286. https://doi.org/10.1080/09515089008573004

Brunet, N., Bosman, C. A., Roberts, M., Oostenveld, R., Womelsdorf, T., De Weerd, P., & Fries, P. (2013). Visual cortical gamma-band activity during free viewing of natural images. *Cerebral Cortex*, *25*(4), 918–926. https://doi.org/10.1093/cercor/bht280

Cardin, J. A., Carlén, M., Meletis, K., Knoblich, U., Zhang, F., Deisseroth, K., Tsai, L.-H., & Moore, C. I. (2009). Driving fast-spiking cells induces gamma rhythm and controls sensory responses. *Nature*, *459*, 663–667.

Casarotto, S., Comanducci, A., Rosanova, M., Sarasso, S., Fecchio, M., Napolitani, M., Pigorini, A., Casali, A., Trimarchi, P., Boly, M., Gosseries, O., Bodart, O., Curto, F., Landi, C., Mariotti, M., Devalle, G., Laureys, S., Tononi, G., & Massimini, M. (2016). Stratification of unresponsive patients by an independently validated index of brain complexity. *Annals of Neurology*, *80*(5), 718–729. https://doi.org/10.1002/ana.24779

Chalmers, D. J. (1996). *The conscious mind: In search of a fundamental theory*. Oxford University Press.

Cohen, M. X. (2017). Where does EEG come from and what does it mean? *Trends in Neurosciences*, *40*(4), 208–218. https://doi.org/10.1016/j.tins.2017.02.004

Cole, E. J., Stimpson, K. H., Bentzley, B. S., Gulser, M., Cherian, K., Tischler, C., Nejad, R., Pankow, H., Choi, E., Aaron, H., Espil, F. M., Pannu, J., Xiao, X., Duvio, D., Solvason, H. B., Hawkins, J., Guerra, A., Jo, B., Raj, K. S., . . . Williams, N. R. (2020). Stanford accelerated intelligent neuromodulation therapy for treatment-resistant depression. *American Journal of Psychiatry*, *177*(8), 716-726. https://doi.org/10.1176/appi.ajp.2019.19070720

Crick, F., & Koch, C. (1990). Towards a neurobiological theory of consciousness. *Seminars in the Neurosciences*, *2*, 263–275.

Darwin, C. (2014). *On the origin of species: By means of natural selection*. Arcturus. (Original work published 1859)

Davis, K. L., & Montag, C. (2019). Selected principles of Pankseppian affective neuroscience. *Frontiers in Neuroscience*, *12*, Article 1025. https://doi.org/10.3389/fnins.2018.01025

Dehaene, S. (2014). *Consciousness and the brain: Deciphering how the brain codes our thoughts*. Penguin.

Dehaene, S., & Changeux, J. P. (2004). Neural mechanisms for access to consciousness. *The cognitive neurosciences*, *3*, 1145–1158.

Dehaene, S., & Changeux, J. P. (2005). Ongoing spontaneous activity controls access to consciousness: A neuronal model for inattentional blindness. *PLOS Biology*, *3*, Article e141. https://doi.org/10.1371/journal.pbio.0030141

Dehaene, S., Changeux, J.-P., Naccache, L., Sackur, J., & Sergent, C. (2006). Conscious, preconscious, and subliminal processing: A testable taxonomy. *Trends in Cognitive Sciences*, *10*, 204–211. https://doi.org/10.1016/j.tics.2006.03.007

Dehaene, S., Kerszberg, M., & Changeux, J. P. (1998). A neuronal model of a global workspace in effortful cognitive tasks. *Proceedings of the National Academy of Sciences, USA*, *95*, 14529–14534.

Dehaene, S., & Naccache, L. (2001). Towards a cognitive neuroscience of consciousness: Basic evidence and a workspace framework. *Cognition*, *79*, 1–37.

Dehaene, S., Sergent, C., & Changeux, J. P. (2003). A neuronal network model linking subjective reports and objective physiological data during conscious perception. *Proceedings of the National Academy of Sciences, USA*, *100*(14), 8520–8525. https://doi.org/10.1073/pnas.1332574100

Demertzi, A., Tagliazucchi, E., Dehaene, S., Deco, G., Barttfeld, P., Raimondo, F., Martial, C., Fernández-Espejo, D., Rohaut, B., Voss, H. U., Schiff, N. D., Owen, A. M., Laureys, S., Naccache, L., & Sitt, J. D. (2019). Human consciousness is supported by dynamic complex patterns of brain signal coordination. *Science Advances*, *5*(2), Article aat7603. https://doi.org/10.1126/sciadv.aat7603

Dennett, D. C. (2008). *Kinds of minds: Toward an understanding of consciousness*. Basic Books.

Dyson, F. (1979). *Disturbing the universe*. Basic Books.

Falkenstein, M., Hoormann, J., & Hohnsbein, J. (2002). Inhibition-related ERP components: Variation with modality, age, and time-on-task. *Journal of Psychophysiology*, *16*, 167–175.

Faugeras, F. (2011). Probing consciousness with event-related potentials in the vegetative state. *Neurology*, *77*, 264–268.

Fischer, C., Luaute, L., & Morlet, D. (2010). Event-related potentials (MMN and novelty P3) in permanent vegetative or minimally conscious states. *Clinical Neurophysiology*, *121*, 1032–1042.

Förster, J., Koivisto, M., & Revonsuo, A. (2020). ERP and MEG correlates of visual consciousness: The second decade. *Consciousness and Cognition*, *80*, 102917. https://doi.org/10.1016/j.concog.2020.102917

Fries, P. (2015). Rhythms for cognition: Communication through coherence. *Neuron*, *88*(1), 220–235. https://doi.org/10.1016/j.neuron.2015.09.034

Gail, A., Brinksmeyer, H. J., & Eckhorn, R. (2000). Contour decouples gamma activity across texture representation in monkey striate cortex. *Cerebral Cortex*, *10*, 840–850.

Gallotto, S., Sack, A. T., Schuhmann, T., & de Graaf, T. A. (2017). Oscillatory correlates of visual consciousness. *Frontiers in Psychology*, *8*, Article 1147. https://doi.org/10.3389/fpsyg.2017.01147

Ghanbari, Z., & Moradi, M. H. (2020). FSIFT-PLV: An emerging phase synchrony index. *Biomedical Signal Processing and Control*, *57*, 101764. https://doi.org/10.1016/j.bspc.2019.101764

Goff, P. (2017). *Consciousness and fundamental reality*. Oxford University Press.

Gray, C. M., & Singer, W. (1989). Stimulus-specific neuronal oscillations in orientation columns of cat visual cortex. *Proceedings of the National Academy of Sciences, USA*, *86*, 1698–702.

Gregoriou, G. G., Gotts, S. J., Zhou, H., & Desimone, R. (2009). High-frequency, long-range coupling between prefrontal and visual cortex during attention. *Science*, *324*, 1207–1210. https://doi.org/10.1126/science.1171402

Griffen, D. (1997). Panexperientialist physicalism and the mind-body problem. *Journal of Consciousness Studies*, *4*(3), 248–268.

Griffin, D. R. (2001). *Animal minds: Beyond cognition to consciousness*. University of Chicago Press.

Groppe, D. M., Bickel, S., Keller, C. J., Jain, S. K., Hwang, S. T., Harden, C., & Mehta, A. D. (2013). Dominant frequencies of resting human brain activity as measured by the electrocorticogram. *NeuroImage*, *79*, 223–233. https://doi.org/10.1016/j.neuroimage.2013.04.044

Hales, C. G. (2017). The origins of the brain's endogenous electromagnetic field and its relationship to provision of consciousness. In *Biophysics of consciousness: A foundational approach* (pp. 295–354). World Scientific. https://doi.org/10.1142/9789814644266_0010

Hermes, D., Miller, K. J., Wandell, B. A., & Winawer, J. (2015). Stimulus dependence of gamma oscillations in human visual cortex. *Cerebral Cortex*, *25*(9), 2951–2959. https://doi.org/10.1093/cercor/bhu091

Hiley, B. J., & Peat, F. D. (1987). *Quantum implications: Essays in honour of David Bohm*. Routledge.

Höller, Y., Kronbichler, M., Bergmann, J., Crone, J. S., Ladurner, G., & Golaszewski, S. (2011). EEG frequency analysis of responses to the own-name stimulus. *Clinical Neurophysiology*, *122*(1), 99–106.

Hunt, T. (2011). Kicking the psychophysical laws into gear a new approach to the combination problem. *Journal of Consciousness Studies*, *18*(11–12), 96–134.

Hunt, T. (2014). *Eco, ego, eros: Essays in philosophy, spirituality and science*. Aramis Press.

Hunt, T. (2016). Taking time seriously in Tononi's integrated information theory. *Journal of Consciousness Studies*, *23*(9–10), 88–110.

Hunt, T. (2019, June 11). Resonance and process philosophy. *Medium*. https://medium.com/@aramis720/resonance-and-process-philosophy-e5b801045ca6

Hunt, T. (2020). Calculating the boundaries of consciousness in General Resonance Theory. *Journal of Consciousness Studies*, *11–12*, 27.

Hunt, T., & Schooler, J. W. (2019). The easy part of the hard problem: A resonance theory of consciousness. *Frontiers in Human Neuroscience*, *13*, Article 378. https://doi.org/10.3389/fnhum.2019.00378

James, W. (1890). *The principles of psychology*. H. Holt.

John, E. R. (2001). A field theory of consciousness. *Consciousness and Cognition*, *10*(2), 184–213.

Jones, M. (2013). Electromagnetic-field theories of mind. *Journal of Consciousness Studies*, *20*(11–12), 124–149.

King, J. R., Sitt, J. D., Faugeras, F., Rohaut, B., El Karoui, I., Cohen, L., Naccahe, L., & Dehaene, S. (2013). Information sharing in the brain indexes consciousness in noncommunicative patients. *Current Biology*, *23*, 1914–1919. https://doi.org/10.1016/j.cub.2013.07.075

Klimesch, W. (2018). The frequency architecture of brain and brain body oscillations: An analysis. *European Journal of Neuroscience*, *48*(7), 2431–2453. https://doi.org/10.1111/ejn.14192

Koch, C. (2004). *The quest for consciousness: A neurobiological approach*. Roberts & Company Publishers.

Koch, C. (2019). *The feeling of life itself: Why consciousness is widespread but can't be computed*. The MIT Press.

Koch, C., & Tsuchiya, N. (2007). Attention and consciousness: Two distinct brain processes. *Trends in Cognitive Sciences*, *11*(1), 16–22. https://doi.org/10.1016/j.tics.2006.10.012

Koivisto, M., & Revonsuo, A. (2010). Event-related brain potential correlates of visual awareness. *Neuroscience & Biobehavioral Reviews*, *34*, 922–934.

Kouider, S., Stahlhut, C., Gelskov, S. V., Barbosa, L. S., Dutat, M., de Gardelle, V., Christophe, A., Dehaene, S., & Dehaene-Lambertz, G. (2013). A neural marker of perceptual consciousness in infants. *Science*, *340*(6130), 376–380. https://doi.org/10.1126/science.1232509

Kumar, S., Gander, P. E., Berger, J. I., Billig, A. J., Nourski, K. V., Oya, H., Kawasaki, H., Howard, M. A., III, & Griffiths, T. D. (2020). Oscillatory correlates of auditory working memory examined with human electrocorticography. *Neuropsychologia*, *150*, 107691. https://doi.org/10.1016/j.neuropsychologia.2020.107691

Lakatos, P., Gross, J., & Thut, G. (2019). A new unifying account of the roles of neuronal entrainment. *Current Biology*, *29*(18), 890–R905. https://doi.org/10.1016/j.cub.2019.07.075

Lakatos, P., Shah, A. S., Knuth, K. H., Ulbert, I., Karmos, G., & Schroeder, C. E. (2005). An oscillatory hierarchy controlling neuronal excitability and stimulus processing in the auditory cortex. *Journal of Neurophysiology*, *94*(3), 1904–1911. https://doi.org/10.1152/jn.00263.2005

Lea-Carnall, C. A., Montemurro, M. A., Trujillo-Barreto, N. J., Parkes, L. M., & El-Deredy, W. (2016). Cortical resonance frequencies emerge from network size and connectivity. *PLOS Computational Biology*, *12*(2), Article e1004740. https://doi.org/10.1371/journal.pcbi.1004740

LeDoux, J. (2019). *The deep history of ourselves: How ancient microbes became conscious brains* [Audiobook]. Penguin Audio.

Leung, A., Cohen, D., Van Swinderen, B., & Tsuchiya, N. (2021). Integrated information structure collapses with anesthetic loss of conscious arousal in *Drosophila melanogaster*. *PLOS Computational Biology*, *17*(2), Article e1008722. https://doi.org/10.1371/journal.pcbi.1008722

Libet, B. (2005). *Mind time: The temporal factor in consciousness*. Harvard University Press.

Mashour, G. A., Roelfsema, P., Changeux, J.-P., & Dehaene, S. (2020). Conscious processing and the global neuronal workspace hypothesis. *Neuron*, *105*, 776–798. https://doi.org/10.1016/j.neuron.2020.01.026

Massimini, M., Boly, M., Casali, A., Rosanova, M., & Tononi, G. (2009). A perturbational approach for evaluating the brain's capacity for consciousness. *Progress in Brain Research*, *177*, 201–214. https://doi.org/10.1016/S0079-6123(09)17714-2

McFadden, J. (2002a). The Conscious Electromagnetic Information (CEMI) field theory: The hard problem made easy? *Journal of Consciousness Studies*, *9*(8), 45–60.

McFadden, J. (2002b). Synchronous firing and its influence on the brain's electromagnetic field: Evidence for an electromagnetic field theory of consciousness. *Journal of Consciousness Studies*, *9*(4), 23–50.

McFadden, J. (2013). The CEMI field theory: Closing the loop. *Journal of Consciousness Studies*, *20*(1–2), 153–168.

Michel, M., Beck, D., Block, N., Blumenfeld, H., Brown, R., Carmel, D., Carrasco, M., Chirimuuta, M., Chun, M., Cleeremans, A., Dehaene, S., Fleming, S. M., Frith, C., Haggard, P., Biyu, J. H., Heyes, C., Goodale, M. A., Irvine, L., Kawato, M., . . . Yoshida, M. (2019). Opportunities and challenges for a maturing science of consciousness. *Nature Human Behaviour*, *3*(2), 104–107. https://doi.org/10.1038/s41562-019-0531-8

Oizumi, M., Albantakis, L., & Tononi, G. (2014). From the phenomenology to the mechanisms of consciousness: Integrated Information Theory 3.0. *PLOS Computational Biology*, *10*(5), Article e1003588. https://doi.org/10.1371/journal.pcbi.1003588

Panksepp, J., & Biven, L. (2012). *The archaeology of mind: Neuroevolutionary origins of human emotions*. W. W. Norton.

Peterson, N. N., Schroeder, C. E., & Arezzo, J. C. (1995). Neural generators of early cortical somatosensory evoked potentials in the awake monkey. *Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section*, *96*(3), 248–260. https://doi.org/10.1016/0168-5597(95)00006-E

Pikovsky, A., Rosenblum, M., & Kurths, J. (2002). *Synchronization: A universal concept nonlinear science*. Cambridge University Press.

Pins, D., & Ffytche, D. (2003). The neural correlates of conscious vision. *Cerebral Cortex*, *13*(5), 461–474. https://doi.org/10.1093/cercor/13.5.461

Pitts, M. A., Martínez, A., & Hillyard, S. A. (2012). Visual processing of contour patterns under conditions of inattentional blindness. *Journal of Cognitive Neuroscience*, *24*(2), 287–303. https://doi.org/10.1162/jocn_a_00111

Pitts, M. A., Metzler, S., & Hillyard, S. A. (2014). Isolating neural correlates of conscious perception from neural correlates of reporting one's perception. *Frontiers in Psychology*, *5*, Article 1078. https://doi.org/10.3389/fpsyg.2014.01078

Pitts, M. A., Padwal, J., Fennelly, D., Martínez, A., & Hillyard, S. A. (2014). Gamma band activity and the P3 reflect post-perceptual processes, not visual awareness. *NeuroImage*, *101*, 337–350. https://doi.org/10.1016/j.neuroimage.2014.07.024

Pockett, S. (2000). *The nature of consciousness*. Writers Club Press.

Pockett, S. (2012). The electromagnetic field theory of consciousness: A testable hypothesis about the characteristics of conscious as opposed to non-conscious fields. *Journal of Consciousness Studies*, *19*(11–12), 191–223.

Railo, H., Koivisto, M., & Revonsuo, A. (2011). Tracking the processes behind conscious perception: A review of event-related potential correlates of visual consciousness. *Consciousness and Cognition*, *20*(3), 972–983. https://doi.org/10.1016/j.concog.2011.03.019

Ray, S., Ni, A. M., & Maunsell, J. H. R. (2013). Strength of gamma rhythm depends on normalization. *PLOS Biology*, *11*(2), Article e1001477. https://doi.org/10.1371/journal.pbio.1001477

Roberts, M. J., Lowet, E., Brunet, N. M., Ter Wal, M., Tiesinga, P., Fries, P., & De Weerd, P. (2013). Robust gamma coherence between macaque V1 and V2 by dynamic frequency matching. *Neuron*, *78*, 523–536. https://doi.org/10.1016/j.neuron.2013.03.003

Saltz, J. (2018, October 25). An artwork made by artificial intelligence just sold for $400,000. I am shocked, confused, appalled. *Vulture.com*. https://www.vulture.com/2018/10/an-artificial-intelligence-artwork-just-sold-for-usd400-000.html

Schelonka, K., Graulty, C., Canseco-Gonzalez, E., & Pitts, M. A. (2017). ERP signatures of conscious and unconscious word and letter perception in an inattentional blindness paradigm. *Consciousness and Cognition*, *54*, 56–71. https://doi.org/10.1016/j.concog.2017.04.009

Schlossmacher, I., Dellert, T., Pitts, M., Bruchmann, M., & Straube, T. (2020). Differential effects of awareness and task relevance on early and late ERPs in a no-report visual oddball paradigm. *Journal of Neuroscience*, *40*(14), 2906–2913. https://doi.org/10.1523/JNEUROSCI.2077-19.2020

Schooler, J. W., Hunt, T., & Schooler, J. N. (2011). Reconsidering the metaphysics of science from the inside out. In H. Walach, S. Schmidt, & W. B. Jonas (Eds.), *Neuroscience, consciousness and spirituality* (pp. 157–194). Springer.

Shafto, J. P., & Pitts, M. A. (2015). Neural signatures of conscious face perception in an inattentional blindness paradigm. *Journal of Neuroscience*, *35*, 10940–10948.

Sitt, J. D., King, J.-R., Karoui, I. E., Rohaut, B., Faugeras, F., Gramfort, A., Cohen, L., Sigman, M., Dehaene, S., & Naccache, L. (2014). Large scale screening of neural signatures of consciousness in patients in a vegetative or minimally conscious state. *Brain*, *137*, 2258–2270.

Steriade, M., McCormick, D. A., & Sejnowski, T. J. (1993). Thalamocortical oscillations in the sleeping and aroused brain. *Science*, *262*, 679–685. https://doi.org/10.1126/science.8235588

Tallon-Baudry, C. (2012). On the neural mechanisms subserving consciousness and attention. *Frontiers in Psychology*, *2*, Article 397. https://doi.org/10.3389/fpsyg.2011.00397

Tiesinga, P., & Sejnowski, T. J. (2009). Cortical enlightenment: Are attentional gamma oscillations driven by ING or PING? *Neuron*, *63*, 727–732. https://doi.org/10.1016/j.neuron.2009.09.009

Tononi, G., Boly, M., Massimini, M., & Koch, C. (2016). Integrated information theory: From consciousness to its physical substrate. *Nature Reviews Neuroscience*, *17*(7), 450–461.

Traub, R. D., Whittington, M. A., Colling, S. B., Buzsáki, G., & Jefferys, J. G. (1996). Analysis of gamma rhythms in the rat hippocampus in vitro and in vivo. *The Journal of Physiology*, *493*(Pt. 2), 471–484.

Tsuchiya, N., & Koch, C. (2009). The relationship between consciousness and attention. *The Neurology of Consciousness*, *2009*, 63–77. https://doi.org/10.1016/B978-0-12-374168-4.00006-X

Tsuchiya, N., Wilke, M., Frässle, S., & Lamme, V. A. (2015). No-report paradigms: Extracting the true neural correlates of consciousness. *Trends in Cognitive Sciences*, *19*(12), 757–770. https://doi.org/10.1016/j.tics.2015.10.002

Turing, A. (1950). *Computing machinery and intelligence*. MIT Press.

Tzovara, A., Simonin, A., Oddo, M., Rossetti, A. O., & De Lucia, M. (2015). Neural detection of complex sound sequences in the absence of consciousness. *Brain*, *138*(Pt. 5), 1160–1166.

Vitale, K. R., Behnke, A. C., & Udell, M. A. (2019). Attachment bonds between domestic cats and humans. *Current Biology*, *29*(18), R864–R865. https://doi.org/10.1016/j.cub.2019.08.036

Walleczek, J. (Ed.). (2006). *Self-organized biological dynamics and nonlinear control: Toward understanding complexity, chaos and emergent function in living systems*. Cambridge University Press.

Winfree, A. T. (1980). *The geometry of biological time*. Springer.

Wyart, V., & Tallon-Baudry, C. (2008). Neural dissociation between visual awareness and spatial attention. *Journal of Neuroscience*, *28*(10), 2667–2679. https://doi.org/10.1523/JNEUROSCI.4748-07.2008

Young, A., Hunt, T., Ericson, M., & Schooler, J. (2019). The slowest shared resonance: A review of the data on shared resonance between brain and peripheral nervous system. *Frontiers in Human Neuroscience*, *13*, Article 378. https://doi.org/10.3389/fnhum.2019.00378

Zhou, H., Schafer, R. J., & Desimone, R. (2016). Pulvinar-cortex interactions in vision and attention. *Neuron*, *89*, 209–220. https://doi.org/10.1016/j.neuron.2015.11.034