What it is like to be a bit: An Integrated Information Decomposition account of emergent mental phenomena

Andrea I. Luppi^{a,b}, Pedro A.M. Mediano^c, Fernando E. Rosas^{d,e,f}, David J. Harrison^{g,h}, Robin L. Carhart-Harris^d, Daniel Bor^{c*}, Emmanuel A. Stamatakis^{a*}

^aDivision of Anaesthesia, School of Clinical Medicine, University of Cambridge, UK

^bDepartment of Clinical Neurosciences, University of Cambridge, Cambridge, UK

^cDepartment of Psychology, University of Cambridge, Cambridge, UK

^dCenter for Psychedelic Research, Department of Brain Science, Imperial College London, London, UK

^eData Science Institute, Imperial College London, London, UK

^fCentre for Complexity Science, Imperial College London, London, UK

^gDepartment of History and Philosophy of Science, University of Cambridge, Cambridge, UK

^hLeverhulme Centre for the Future of Intelligence, University of Cambridge, Cambridge, UK

^{*i}These authors contributed equally to this work.

Correspondence: Andrea I. Luppi. Email: al857@cam.ac.uk

Abstract:

A central question in neuroscience concerns the relationship between consciousness and its physical substrate. Here, we argue that a richer characterisation of consciousness can be obtained by viewing it not as a monolithic construct, but rather as constituted of distinct information-theoretic elements. In other words, we propose a shift from quantification of consciousness - viewed as integrated information - to its decomposition. Through this approach, termed Integrated Information Decomposition (Φ ID), we lay out a formal argument that whether the consciousness of a given system is an emergent phenomenon depends on its information-theoretic composition - thus providing a principled answer to the long-standing dispute on the relationship between consciousness and emergence. Furthermore, we show that two organisms may attain the same amount of integrated information, yet differ in its information-theoretic composition. Building on Φ ID's revised understanding of integrated information, termed Φ_R , we also introduce the notion of Φ_R -ing rate to quantify how efficiently an entity uses information for conscious processing. A combination of Φ_R and Φ_R -ing rate may provide an important way to compare the neural basis of different aspects of consciousness. Thus, decomposition of consciousness enables us to identify qualitatively different 'modes of consciousness,' which establish a common space for mapping the phenomenology of different conscious states. We outline both theoretical and empirical avenues to carry out such mapping between phenomenology and information-theoretic modes, starting from a central feature of everyday consciousness: selfhood. Overall, Integrated Information Decomposition yields rich new ways to explore the relationship between information, consciousness, and its emergence from neural dynamics.

Introduction

A central aim in both neuroscience and philosophy of mind is understanding the relationship between consciousness and its physical substrate. The past two decades have seen a proliferation of theoretical, experimental, and philosophical work on this topic (Crick & Koch 2003; Friston 2012; Tononi & Koch 2015; Koch et.al. 2015; Tononi et.al. 2016; Parr & Friston 2019; Kleiner 2020). Additionally, an important and related question to how consciousness arises from matter concerns a mathematically precise and conceptually clear account of what constitutes ‘emergence’ (Tononi Sporns Edelman 1998; Friston et.al. 2014; Hesp et.al. 2019; De Caro & Grasso 2017; Palacios et.al. 2020; Palacios et.al. 2019; Cea 2020). The present work is situated at the convergence of these two fundamental research avenues: that is, in this paper we seek to contribute to the formalisation of the relationship between consciousness and its underlying physical substrate, and elucidate to what extent this relationship can be rigorously understood in terms of emergence. To this end, we demonstrate the value of leveraging novel information-theoretic approaches to shed light on the nature of consciousness.

Here, we understand consciousness to be that, which is lost during dreamless sleep and deep anaesthesia, and recovered upon awakening (Schwitzgebel 2016). Following William James’s celebrated notion of the stream of consciousness, we take the stance that subjective experiences dynamically unfold over time. For this reason, when seeking to understand the aspects of the physical world that correspond to subjective experiences, and give rise to them, we direct our attention to neural dynamics. Indeed, neural dynamics have recently been proposed as a “common currency” between brain and mind (Northoff et al., 2020), and a growing body of empirical work has demonstrated - through a variety of neuroimaging modalities and analytic approaches - that considering neural dynamics can provide powerful insights into consciousness and its alterations (Barttfeld et al., 2015; Deco et al., 2019; Demertzi et al., 2019; Dinesh et.al. 2020; Huang et al., 2020; Lee et al., 2019; Lord et al., 2019; Standage et al., 2020; Uhrig et al., 2018; Atasoy et.al. 2017; Atasoy et.al. 2018; Luppi et.al. 2019; Luppi et.al. 2020b-d; Vlisides et al., 2019; Varley et al., 2020a,b).

Thus, both theoretical and empirical reasons lead us to adopt a process-theoretic framework to the study of consciousness. Shannon’s information theory is particularly well-suited to address process-theoretic approaches such as the one adopted here, because it enables the study of dynamical processes in a way that is not committed to any specific physical instantiation. This is not to say that the physicality of the system does not matter for the instantiation of consciousness: some material substrates may be more or less suitable (e.g., in terms of degrees of freedom) to sustain the dynamics on which consciousness depends (see esp. Barrett 2014). Rather, information theory enables us to focus on the dynamics and their properties, abstracted from considerations about physical instantiation or neuroimaging modality.

From quantification of consciousness to its decomposition

The close relationship between consciousness and information is a key aspect of the well-known Integrated Information Theory of consciousness (hereafter, IIT) (Tononi et.al. 1994; Balduzzi & Tononi 2008). A core intuition from IIT is that the “integration of information” represents a fundamental aspect of consciousness - and therefore, quantifying integrated information (suitably defined, as we explore in ‘Technical preliminaries’ below) enables an effective quantification of consciousness.

Quantification is a key step in the scientific process, and the notion that consciousness could be quantified has contributed in no small part to the scientific study of consciousness in the last two decades. After quantification, decomposition into fundamental elements can be a fruitful next step in the scientific process, driving major advances in fields such as physics and chemistry over the last two centuries. As an illustrative example, knowing whether the clear liquid in one's glass is composed by twice as much hydrogen as oxygen, or oxygen and hydrogen in equal parts, represents the difference between drinking refreshing water or poisonous hydrogen peroxide. We believe that understanding the information-theoretic composition of consciousness will be similarly crucial for its scientific characterisation.

Within this context, the aim of this paper is to shed light on consciousness from an information-theoretic perspective by capitalising on major advances in information theory, specifically within the recent framework of Partial Information Decomposition (PID) (Wibral et.al. 2017; Bertschinger et.al. 2014; Griffith & Koch 2014; Lizier et.al. 2018) and its multivariate extension, Integrated Information Decomposition (Φ ID) (Mediano et.al. 2019). Shannon's seminal results on information theory are mainly focused on information transmission between a single source and a single target; Partial Information Decomposition extends classic information-theoretic approaches to systems involving multiple sources of information (Wibral et.al. 2017). Moreover, the more recent development of Integrated Information Decomposition further extends PID to scenarios involving multiple targets as well as multiple sources (Mediano et.al. 2019). Such an extension is necessary if we are to investigate complex, multivariate systems with intricate causal relationships, of which the human brain is a prime example (Varley et al., 2020b; Turkheimer et.al. 2020). Thus, information decomposition - and Φ ID in particular - proves especially valuable for our purposes, being ideally suited to accommodate the multifaceted dynamics that characterise neural activity.

Here we propose a paradigm shift beyond the quantification of consciousness, and towards its decomposition into fundamental information-theoretic elements. For this purpose, we explore the consequences of viewing the core intuition that consciousness can be quantified in terms of integrated information in the light of Integrated Information Decomposition. (Note that we are not thereby committed to any of IIT's additional theoretical positions: for instance, we remain agnostic on whether integrated information is identical with consciousness, or co-extensive with it under certain descriptions). Hence, a key goal of the present work is to demonstrate that understanding the composition of consciousness in terms of its information-dynamic building blocks may be crucial to obtain insights about what consciousness is - and the various modes in which it can be configured. Another major goal is the formal demonstration that consciousness can comprise both emergent and non-emergent phenomena - which can only be determined based on its information-theoretic composition.

We call this Φ ID-based approach to consciousness "Psy-ID" (Ψ ID), as it is the result of an application of Φ ID to psychological phenomena. Importantly, this framework also sheds new light on other prominent theories of consciousness such as the Global Neuronal Workspace Theory (Dehaene & Changeux 2011; Mashour et.al. 2020) by providing an information-theoretic definition of the workspace in terms of synergistic interactions (Luppi et.al. 2020b). In contrast to other theoretical accounts of consciousness, Ψ ID provides a formal framework that is applicable to neuroimaging data, which enables a range of practical investigations on such observed dynamics (Mediano et.al. 2019; Luppi et.al. 2020a,b). This is especially important because we take it as imperative to our theoretical endeavours to provide predictions about consciousness that can be tested - and possibly falsified - by our current neuroimaging methods.

The rest of this paper is structured as follows. First, ‘Technical preliminaries’ provides an accessible overview of the main information-theoretic intuitions and basic premises on which our work builds. Then, ‘Theoretical contributions’ introduces Ψ ID to explicate the ramifications of Φ ID for understanding consciousness and the neural dynamics on which it depends. Therein, we specify core terminology that is relevant to the hypotheses and predictions we propose in the third section, ‘Empirical predictions.’ In this final section, we explore testable hypotheses and predictions as applied to recent experimental work on psychedelics and consciousness. This paper concludes with a series of remarks on the implications of Ψ ID and its potential limitations.

Technical preliminaries

This section develops the formal intuitions and basic premises behind Integrated Information Theory, from which our paper takes its start. We then follow with an elaboration of the PID framework and its extension to IIT, called Φ ID.

The mind’s Φ : Integrated Information Theory

The starting point of our investigation is the notion that consciousness can be quantified in terms of the integrated information of a system - the fundamental intuition of Integrated Information Theory (Tononi 2004; Balduzzi and Tononi, 2008). Stemming from the seminal ideas put forward by Tononi, Sporns and Edelman (1994), IIT’s core premise (which we share) is that the brain can be comprehensively characterized by its dynamics - i.e. the way in which the brain’s activity unfolds over time (Tononi & Edelman 1998; Northoff et al., 2020). Correspondingly, these dynamics allow the brain’s current state to contain some information about its past and future states. Mathematically, this information that “flows” from the past to the future of a dynamical system can be captured by the so-called time-delayed mutual information (TDMI) (Barrett & Seth 2011), denoted as $I(X_t; X_{t+1})$, where X_t and X_{t+1} indicate the state of the system at consecutive times t and $t+1$. Broadly speaking, TDMI provides a first step towards quantifying the dynamical structure of a complex system (James et.al. 2011).

A further refinement on this idea is to consider not only the overall amount of information, but also its spatiotemporal distribution. Different parts of the brain exchange information constantly - and the existence and relevance of these precise informational patterns is uncontroversial in cognitive neuroscience. Moreover, although a precise, theoretically-based measure remains to be discovered, there is mounting evidence that the patterns of information that spread across the brain are related to consciousness (Casali et.al. 2013; Luppi et.al. 2020b).

One of the key insights of Tononi, Sporns and Edelman was to realise that this information must be shared across the brain in particular ways, such that it is simultaneously integrated (so the brain can behave as a whole) and differentiated (so its parts can perform independent processing). These ideas materialised into specific formulae to quantify integration and differentiation in the brain. In particular, the first such quantity to explicitly include the brain’s dynamics into its formulation was the measure of integrated information proposed by Balduzzi & Tononi (2008),

166

$$\Phi = I(X_t; X_{t+1}) - \sum_{i=1}^n I(X_t^i; X_{t+1}^i)$$

167 As above, here X_t denotes the state of the system as a whole at time t ; X_t^i denotes the i^{th} part of
 168 X at time t (and likewise for X_{t+1} and X_{t+1}^i). Thus, this measure compares the information flow
 169 between past and future (as captured by TDMI) observed in the whole system X , with the flow
 170 observed within each of its parts - for this reason it is also referred to as “whole-minus-sum”
 171 Φ (Mediano et al., 2019). This measure is easy to compute (compared with other Φ measures)
 172 (Oizumi et.al. 2016), and represents a noteworthy attempt to capture the powerful intuitions
 173 behind IIT. However, this mathematical formulation has known shortcomings, including the
 174 fact that it can yield negative values in some cases - which are hard to interpret, as a system
 175 cannot intuitively be “negatively integrated” or have negative consciousness (Oizumi et.al.
 176 2016; Mediano et.al. 2018) . In the following, we show how these shortcomings can be
 177 overcome by means of the mathematical framework of Integrated Information Decomposition.

178 Information decomposition

179 The time-delayed mutual information on which Φ depends, is a special case of Shannon’s
 180 mutual information, I . On a conceptual level, this “information” can be understood in several
 181 distinct but converging ways (Shannon 1948; Hellman & Raviv 1970; Feder & Merhav 1994;
 182 Jaynes 2003; Parrondo et.al. 2015). While extremely versatile, Shannon’s information theory
 183 is (mainly) confined to interactions between pairs of variables (e.g. a sender and a receiver),
 184 and it is not equipped to study the information that multiple parts of a system have about each
 185 other’s dynamical evolution.

186 Part of the necessary technical equipment for such analysis was introduced by Williams and
 187 Beer (2010) with their framework of Partial Information Decomposition (PID). PID, in short,
 188 decomposes the total information that two sources give about a target into four distinct “*partial*
 189 *information atoms*,” typically called *synergistic*, *redundant*, and *unique* information (note that
 190 for the sake of simplicity, throughout this work we will only consider the case of bivariate
 191 systems: for details of generalisation to more than two variables, we refer the reader to Mediano
 192 et. al (2019)).

193 As an illustrative example of redundant, unique and synergistic information, consider humans’
 194 two sources of visual information about the world: the eyes. The two eyes provide in part the
 195 same information, which is the information that is not lost when closing one or the other eye.
 196 This information is therefore carried redundantly by both sources. However, information about
 197 the very edge of the visual field is unique to each eye: this unique information is lost when the
 198 corresponding eye is closed. Finally, closing either eye will also remove stereoscopic
 199 information about depth: this information is not carried by either eye alone, but rather it requires
 200 both eyes together, arising synergistically from their interaction.

201 Thus, it is important to note that atoms are ways in which the information is being carried, and
 202 should not be confused with the sources of information that are doing the carrying, nor with
 203 the specific content that is being carried: any reference to e.g. “synergy” or “redundancy”
 204 should be understood as short-hand for “information carried synergistically” and “information
 205 carried redundantly,” and likewise for other atoms. Therefore, as a way of example, if both my
 206 eyes show me that there is a red apple in front of me, then each eye (source) is carrying

207 redundantly (atom) information about an apple (target), with the information in question being
208 that the apple is red (content).

209 By allowing us to distinguish qualitatively different phenomena involving multiple information
210 sources that cannot be disentangled by classic information theory (Rosas et.al. 2016), PID
211 moves beyond Shannon's information theory (James & Crutchfield 2017). These novel
212 capabilities of PID have found fruitful application in multiple areas of neuroscience, from spike
213 trains to whole-brain dynamics (Stramaglia et.al. 2014; Wibral et.al. 2017).

214 Decomposing information flow

215 Thanks to the new lens provided by PID, it is now possible to decompose the information that
216 the past state of each part of the system, $X_t^1, \dots, X_t^n$, carries about the future of the whole
217 system, X_{t+1} . Formally, for a system with $n = 2$ parts, PID states that the information that part
218 i has about the future of the system can be decomposed as

$$219 \quad I(X_t^i; X_{t+1}) = \text{Red}(X_t; X_{t+1}) + \text{Un}_i(X_t; X_{t+1}),$$

220 where $\text{Red}(X_t; X_{t+1})$ is the so-called *redundant information* provided by the sources (here, the
221 parts of the system), and $\text{Un}_i(X_t; X_{t+1})$ is the information that X_t^i provides uniquely. Similarly,
222 the joint mutual information (i.e., information that the past state of the system as a whole carries
223 about its future) is decomposed as

$$224 \quad I(X_t; X_{t+1}) = \text{Red}(X_t; X_{t+1}) + \text{Un}_1(X_t; X_{t+1}) + \text{Un}_2(X_t; X_{t+1}) + \text{Syn}(X_t; X_{t+1}).$$

225 Here we see that in addition to redundancy and unique atoms, this expression includes
226 $\text{Syn}(X_t; X_{t+1})$, which accounts for the so-called *synergistic* information: information provided
227 by both sources jointly, but not separately (Fig. 1a).

228

Figure 1. Visual representation of the relationships between PID and Φ ID atoms for bivariate systems. In both cases, to aid visualisation, atoms are arranged into a lattice, a mathematical construct which represents a hierarchical organisation of information content, such that redundant information (held by every variable) is at the bottom, and synergistic information (held only by the whole) is at the top. Please note that while here we focus in the case of two source variables, this information decomposition can be carried out over an arbitrary number of sources - which leads to a more elaborate lattice. For details of this more general construction we refer the reader to (Williams 2011).

Thus, PID provides the means to understand how each part of the system carries information about the future state of the system as a whole, decomposing this information flow into redundant, unique, and synergistic contributions. However, a key drawback of PID is that, while it is naturally applicable to multiple source variables, it can only be applied to scenarios with a single target. Thus, within the PID framework the future state of the system is still considered as a monolithic entity, without being able to consider the future state of each part individually. To resolve this shortcoming and extend the range of applicability of PID, Mediano et al. (2019) put forward the framework of Integrated Information Decomposition (Φ ID), which forms the mathematical basis of our proposal. Formally, Φ ID is a multi-target extension of PID, that can identify the redundant, unique, and synergistic components of the information that multiple source variables carry about multiple target variables.

Specifically, the information that is carried as each of the original four PID atoms (*Red*, *Un*₁, *Un*₂, and *Syn*, see Fig. 1a) at one point in time, at the next point in time may be carried as the same atom, or as any of the other atoms. Therefore, there are $4 \times 4 = 16$ combinations of PID atoms (Fig 1b), which correspond to the decomposition established by Φ ID. For instance, $Un_1 \rightarrow Syn$ denotes the information that is initially carried uniquely by the first source, and subsequently becomes carried synergistically. For more details about the interpretation of each

of the Φ ID atoms, and the generalisation to more than two variables, we refer the reader to Mediano et. al (2019).

Taken together, PID and Φ ID constitute valuable tools to refine our understanding of information processing in dynamical systems - and, therefore, can be used to refine our theories of any phenomenon that depends on such information processing, like consciousness. In the same way as PID allows us to refine our understanding of mutual information, we will see that Φ ID allows us to refine our understanding of Φ .

Refining Φ through Φ ID

Φ ID makes it possible to decompose the information flow between the past and future states of each part of a system. Thus, a key feature of Φ ID for our purposes is that it makes PID applicable to dynamical processes - including neural dynamics. A growing body of recent work has demonstrated that considering dynamical aspects of the brain can shed critical light on various aspects of consciousness (Northoff, 2020). For example, it has been shown that brain dynamics are significantly altered when consciousness is suppressed by anaesthesia or severe brain injury (Luppi et.al. 2019; Luppi et al., 2020; Huang et al., 2020; Demertzi et al., 2019; Barttfeld et al., 2015), or altered by psychedelics (Atasoy et al., 2017, Lord et al 2019, Luppi et al., 2020c, Luppi et al., 2020d). These results highlight the key role of neural dynamics for consciousness, vindicating the approach adopted by Tononi, Sporns, and Edelman (1998).

Specifically, Φ ID allows us to decompose the total information flow from past to future (TDMI, introduced above as $I(X_t; X_{t+1})$) into a range of modes of information dynamics, which can be used to deepen our understanding of various dynamical phenomena observed in the brain. A deeper understanding of Φ and its drawbacks, such as the reasons why it can adopt negative values, can be gained by decomposing it into its constituent information atoms.

Let's recall that Φ ID decomposes the TDMI of a dynamical system with two parts into 16 disjoint atoms (illustrated in Fig. 1(b)). Of those 16 atoms, it can be shown mathematically (Mediano et al., 2019) that 10 are represented in Φ (Fig. 2a): 7 correspond to all the synergistic information in the system, 2 correspond to the information transferred from one part to the other, and, importantly, one redundancy atom with a negative sign. Through this decomposition of Φ one can understand why Φ can sometimes take negative values: the subtraction of the redundancy atoms implies that Φ will be negative in redundancy-dominated systems, whenever redundancy is greater than the sum of synergy and information transfer. Note that transfer and synergy are rather different phenomena: while transfer refers to information that "moves" from one variable to another, synergy corresponds to phenomena that involve both variables, but cannot be seen in any of them when they are examined separately (Mediano et al., 2019).

Leveraging Φ ID, a revised measure of Φ , termed " Φ_R ", can then be formulated by focusing on the synergy and transfer components and dropping the negative redundancy atom from the definition of integrated information (Mediano et al., 2019). Specifically, Φ_R is the sum of synergistic and transfer atoms, and it is thereby guaranteed to be non-negative. Thus, the information decomposition of Φ provided by Φ ID can successfully identify the source of Φ 's theoretical difficulties, and provide a straightforward solution. In addition to the theoretical improvement (which will be further discussed below, in the section "A tale of ice and Φ_R : From neural dynamics to the Φ_R -ing rate"), there is also recent evidence that Φ_R also provides

empirical advantages over the original formulation of Φ : unlike Φ , Φ_R is reduced between the same sets of brain regions both in patients with chronic disorders of consciousness, and during loss of consciousness induced by the intravenous anaesthetic, propofol (Luppi et al., 2020b). Importantly, reductions in Φ_R were reversed when participants recovered consciousness after anaesthesia, demonstrating the relevance of Φ_R for supporting human consciousness. Thus, given the theoretical advantages of Φ_R over Φ outlined here, as well as these recently demonstrated empirical benefits (Luppi et al., 2020b), we will consider Φ_R as our primary metric of integrated information and conscious level throughout the rest of this work.

Figure 2. Φ ID lattice with relevant atoms for Φ (a) and causal emergence (b) highlighted in colour.

A deepness in the Φ : Quantifying causal emergence

Another important feature of Φ ID is that it provides a mathematical framework to build a formal, quantitative definition of causal emergence (Rosas et.al. 2020). Technically, the Φ ID account of causal emergence rests on the following definitions. First, we say that a feature V_t is *supervenient* on the instantaneous state of the system at time t , (denoted by X_t) if V_t is a function of X_t , so that there is nothing about V_t that can be predicted from the system's previous state, X_{t-1} , that cannot be already predicted from the system's current state, X_t . Then, we say that a supervenient feature V_t is *causally emergent* if it has predictive power about the future evolution of X_t that is unique (in the PID sense) with respect to $X_t^1, \dots, X_t^n$.

Causal emergence is therefore defined here as the property of supervenient features to provide predictive power that cannot be explained from underlying microscale phenomena. In this manner, the coexistence of supervenience and irreducible predictive power of emergence - that have been previously thought as paradoxical (Bedau 1997, 2002) - can be resolved by operationalising supervenience in terms of instantaneous relationships between the system and its features, and identifying emergence with predictive power across time. Thus, a feature could be supervenient without being causally emergent, but not *vice versa*.

Crucially, the unique predictive power enabled by emergent features is quantified by Φ ID. It is possible to prove that, under relatively general assumptions (Rosas et.al. 2020), a system's capacity to host causally emergent features depends directly on how synergistic are the system's dynamics. Furthermore, Φ ID allows us to distinguish two qualitatively different types of emergence: *downward causation*, in which an emergent feature has unique predictive power over individual parts; and *causal decoupling*, in which it has unique predictive power not over any constituent, but only over the system as a whole (Fig. 2b and Fig. 3).

Figure 3. Causal decoupling and downward causation as two different types of emergent phenomena.

Interestingly, causal decoupling corresponds to the persistent synergies in the system (top atoms in the Φ ID lattice of Fig. 2b), which can be thought of as “the macroscale having causal influence on the macroscale, above and beyond the microscale effects” (Rosas et al., 2020) (Figure 2b). Microscale and macroscale are then related by downward (macro-to-micro) causation, as well as upward (micro-to-macro) causation, which respectively correspond to transformations of information from and to synergy. The distinction between supervenience and emergence (i.e., causal decoupling and downward causation) is also illustrated in Figure 3.

Theoretical contributions: Ψ ID

To recapitulate, the aim of the present work is to provide a shift from the quantification of consciousness (viewed as integrated information) to its decomposition, and demonstrate how understanding consciousness in terms of Φ ID atoms can shed light on several aspects of consciousness, including its relationship with emergence. If the close relationship between mental and neural dynamics assumed here turns out to be correct, and integrated information (Φ_R) happens to be a valid metric of conscious level, then our Ψ ID framework is ideally suited

to provide insight on the role of the different “modes” of neural dynamics - as determined by the Φ ID atoms - in supporting various aspects of mental phenomena.

Rising Φ_R : quantifying consciousness as an emergent property

There has been abundant and vigorous philosophical debate over whether consciousness is an emergent phenomenon (Feinberg & Mallat 2020). By (i) understanding consciousness as integrated information, (ii) decomposing it into its constituent information-theoretic atoms through Φ ID, and then (iii) viewing those atoms in terms of causal emergence, we are in a position to establish a grounded, formal, and falsifiable way to address this problem - representing the first core contribution of this paper.

In order to fully develop this argument, let’s start noting that the Φ ID decomposition of Φ_R in Figure 2a and of emergence in Figure 2b shows that consciousness (quantified by Φ_R) comprises the atoms of emergence among its constituents, but also comprises additional atoms that are beyond the scope of emergence. The implications of this mathematical fact are profound and far-reaching. In effect, note that nothing in IIT or Φ ID mandates that a given system should exhibit *all* atoms that constitute Φ_R in order to be conscious: all that is required is the presence of at least one of Φ_R ’s constituent atoms with non-zero value. Following this rationale, we can draw two conclusions about the relationship between consciousness and emergence:

1. Consciousness (integrated information) *can* be an emergent phenomenon: there could be systems whose Φ_R derives (entirely or in part) from emergent Φ ID atoms.
2. Consciousness *doesn’t have* to be emergent: there could also be systems whose Φ_R derives entirely from Φ ID atoms that do not enter into the composition of emergence (e.g. information transfer, or non-emergent synergy atoms).

Therefore, thanks to our information-decomposition approach to both consciousness and emergence, we can now see that the original question “Is consciousness an emergent phenomenon” was *fundamentally ill-posed*. Specifically, it was ill-posed because neither consciousness nor emergence are monolithic constructs, but rather they are both constituted by multiple information-theoretic atoms, and - crucially - only some of the atoms that constitute integrated information are emergent. Once this is understood, the answer becomes clear: some possible kinds of consciousness are emergent, others are not, and others may comprise both emergent and non-emergent atoms - in a way that is amenable to empirical investigation.

A tale of ice and Φ_R : From neural dynamics to the Φ_R -ing rate

Decomposing Φ_R can also provide another important insight about the nature of consciousness. Since not all atoms enter into the composition of Φ_R , dynamical processes with the same total amount of information flow (quantified by the time-delayed mutual information, TDMI) can still differ in their Φ_R , and - conversely - organisms with the same Φ_R can differ in TDMI (Figure 4). The proportion of TDMI that is accounted for by Φ_R , which we may refer to as the *Φ_R -ing rate*, can then be thought as quantifying the efficiency with which the organism transforms information into consciousness - its “nougentic rate”. In other words, cognitive architectures can differ in the “consciousness bang” that they provide for a given “informational buck.”

Figure 4. Differences in Φ_R and Φ_R -ing rate. Four conscious beings are schematically depicted as icebergs, with their total size representing their total information (TDMI), the part above water (light blue) representing the combination of atoms that compose Φ_R , and the part below water being the information that does not contribute the Φ_R (and hence to consciousness). Different beings can have the same Φ_R despite different total information (A and B), or same total information but different Φ_R and Φ_R -ing rate (B and C), or different total information and different Φ_R but same Φ_R -ing rate (B and D). Only considering Φ_R would ignore the difference between A and B, as well as the similarity between B and D.

Note that the Φ_R -ing rate is in one respect closer than Φ_R to the original formulation of Φ , in terms of scaling negatively with redundancy. Original Φ explicitly removed redundancy from the quantification of integrated information, but this led to the theoretical flaw that the resulting quantity was not guaranteed to be lower-bound by zero, and could instead be negative if redundancy dominated the system (see Section Refining Φ through Φ_{ID}). Being predicated as the ratio of Φ_R to TDMI, the Φ_R -ing rate implicitly takes redundancy into account, as a component of TDMI; in fact, the more redundancy there is in a system, the lower the Φ_R -ing rate will be even if Φ_R is high overall. In other words, both Φ and the Φ_R -ing rate acknowledge that there is an intuitive difference between a system where much of the information is redundant, and one that instead prioritises dynamics related to consciousness (Φ_R), and is therefore efficient in its ability to turn information into consciousness. The relationship between Φ and Φ_R is illustrated in Figure 4.

At this stage we will not take a stance on whether the part of TDMI that does not contribute to Φ_R (e.g. the redundancy) is to be completely ignored from the study of consciousness - other than as contributing to the calculation of the Φ_R -ing rate - or whether perhaps it could be regarded as “preconscious” or “potential consciousness.”

Thus, we argue that it can be beneficial to characterise information-processing systems with both Φ_R and Φ_R -ing rate, since they provide complementary views on integration information. Therefore, it should be clear that our proposed Φ_R -ing rate is not intended to replace Φ_R , but rather to complement it, thereby enabling a more encompassing framework for quantifications of consciousness.

Carved from Φ_R : Carving consciousness at its joints

Following a similar reasoning, an even more fundamental observation afforded by information decomposition is that even when two systems have the same Φ_R and the same Φ_R -ing rate, they may be entirely different in the composition of their Φ_R . In fact, no single Φ ID atom is essential for Φ_R , suggesting that *two systems may have the same Φ_R despite not sharing any of its constituent atoms* (e.g., a purely emergent system versus a transfer-only system). This possibility raises the fundamental question of whether different Φ ID atoms may correspond to *different ways of being conscious*.

Implicitly, IIT is committed to an affirmative answer to this question: some Φ ID atoms – it posits – are experienced and contribute to the system’s consciousness (integrated information), while other atoms are not: there is nothing it’s like to instantiate those atoms. This stance, however, acknowledges only the coarser aspects of being conscious: namely, being conscious or not at all. In contrast, Ψ ID suggests a richer perspective on this issue, by raising the possibility that different information-theoretic atoms may correspond to fundamentally different ‘ways of being conscious’ - or, as we call them, *modes of consciousness*: broad-strokes aspects of how consciousness is subjectively experienced, which may be more or less extended in time.

Illustrative examples of specific modes of consciousness may include the selflessness experienced during deep meditation or under the effects of psychedelic drugs; or the general way that depression may feel to those suffering from it (see Colombetti & Ratcliffe 2012; Seth & Friston 2016 ; Deane 2020; Deane et al., 2020). Therefore, this is *not* the same as the notion of “qualia”, which instead identify specific and fine-grained aspects of individual conscious experience (the redness of a particular apple; the painfulness of a stubbed toe). Although an IIT-based interpretation of qualia in terms of information geometry and category theory exists (Balduzzi & Tononi 2009; Tsuchiya et.al. 2016; Moon & Pae 2019) and a reinterpretation of this issue through the lens of Φ ID may be possible, this is not our aim here. Note also that although empirical evidence suggests that different cognitive functions rely on different information-theoretic atoms (Luppi et.al. 2020a), our focus here is on altered states of consciousness, rather than normal fluctuations within day-to-day cognitive states.

In other words, Ψ ID contends that beyond the total amount of integrated information in an organism, additional insight may be gleaned from knowing its specific information-theoretic composition, which can be investigated through Φ ID. By investigating the phenomenology associated with specific atoms, these “modes of consciousness” may provide a way to

eventually understand the phenomenology of different states of consciousness from the third-person perspective - as explained below.

What it is like to be a bat

To demonstrate how Ψ ID can enrich our understanding of consciousness, we contend that if integrated information is an effective measure of conscious level, then the corollaries obtained from Ψ ID would bring us one step closer to addressing the famous conundrum that has dogged the philosophy of mind: “What it is like to be a bat”. That is, even though we elect to use the term *modes of consciousness*, and this term is different in its extension from the debate on qualia (for which Nagel’s paper (1974) is typically placed as the cornerstone), it may still allow progress in that matter.

The alchemists of old sought to turn lead into gold, and failed mainly because their understanding of these substances reached only the level of their surface properties (shiny or dull, yellow or grey). Today, thanks to our understanding of atomic composition, turning lead into gold via nuclear transmutation is feasible (though not financially wise). Likewise, Ψ ID may represent a similar change of reference frame for our understanding of consciousness: rather than talking of “human consciousness” or “bat consciousness” tout court (like alchemists conceived of gold and lead as “substances”), we propose that it may be a more proficuous avenue to consider their respective atomic constitutions in terms of Φ ID, and think in terms of information atoms rather than “molecules.” Put differently, rather than trying to perform the mental “human-to-bat” conversion all at once, as Nagel proposed, an atomic understanding of integrated information may provide us with a Rosetta stone to guide a more nuanced comparison.

More generally, we claim that thinking in terms of ‘modes’ or ‘kinds’ of consciousness may be advantageous for the exploration of conscious states within and potentially also across organisms. From this point of view, the work of Nagel may be seen as shaping the debate too narrowly, focusing the discussion on fine-grained aspects of being a bat (flying through the air, echolocating its prey, etc); when it is unclear how much progress can be made from such a starting point towards truly understanding ‘what it’s like to be a bat’. We contend that failure to solve the question on Nagel’s terms should not prescribe scientific pessimism, as it does not follow that *every* aspect of bat consciousness is foreclosed from investigation. In fact, we claim that while the fine-grained details related to contents associated with certain qualia may be highly specific - and hence possibly incommensurable, one might still be able to compare the broad-stroke modes. Indeed, if our approach proves viable, then there may be relevant inferences to be drawn in comparing quantified modes of consciousness via their corresponding Φ ID atoms between different systems, which could lead to insightful phylogenetic or cognitive similarities between conscious creatures.

To illustrate this point, let us focus on the challenge of seeking a Φ ID atomic decomposition of “what it is like to be a human experiencing an altered state of consciousness,” which can be thought as a first step paving a road towards addressing conscious experiences of other species. An atomic understanding of what it may be like to be in a given state of altered consciousness is based on three elements.

1. A description of the atomic composition of the integrated information generated by the human cognitive architecture under baseline conditions, to act as a reference point (although it should be noted that the question of defining a “baseline human state” is itself not trivial, as even so-called “resting state” may be better understood as “Random Episodic Spontaneous Thought”) (Breakspear et al., 2004).
2. A description of the atomic composition of the integrated information generated in a particular state of interest. (If no Φ_R is generated, then the question would be solved with the trivial answer “nothing”, which might be the case for the alterations of consciousness induced by anaesthesia or disorders of consciousness, and indeed there is ongoing empirical research on this topic; see Luppi et.al. 2020b).
3. An understanding of what kind of changes in consciousness may correspond to each observed change of the atoms that constitute Φ_R .

Given these three pieces of information, we may be able to chart the atomic composition of baseline and altered human consciousness in a common Φ ID space (an example of this is shown in Figure 5).

Figure 5. A low-dimensional representation of the information-theoretic atomic compositions of different systems. Each system (here, one shown in blue, the other in red) has a value for each of the three axes (which here summarise the full atomic composition) Synergy-containing atoms and information transfer are the two constituent elements of Φ_R . The sum of a system’s projections on each axis represents its total information flow (TDMI).

The atomic composition of Φ_R may be found empirically by identifying an appropriate level at which neural information operates, and then quantifying the prevalence of each atom in the human brain at baseline and during altered states of consciousness. While this endeavour is far from straightforward, there is at least a plausible understanding of how we may address this challenge. Importantly, while current neuroimaging techniques might not be able to provide a description at the desirable level of resolution, it is still possible for them to provide a trustworthy reflection of the lower level. Hence, the main challenge is finding out what each atom of Φ_R is like, i.e. find a phenomenological answer to “what it is like to be a bit”. The combination of Φ ID with phenomenological interpretations of information-theoretic atoms is therefore the core of our proposed framework, Ψ ID.

Here we propose different (but potentially complementary) strategies that could be followed to identify which modes of consciousness could correspond to each of the atoms of Φ_R . One avenue is to consider altered states of consciousness that one may expect to show an abundance - or lack of - specific atoms, and understand how these differences might be reflected in the corresponding phenomenological alterations. These differences may be due to alterations induced by drugs (e.g., psychedelics, anaesthesia), neurological conditions, or even regular physiological alterations such as sleep, dreaming or meditation. For instance, deep meditation and psychedelics such as LSD can produce a state characterized by “loss of self”, or “ego dissolution”, and we may seek to identify which Φ ID atoms or combination thereof correspond to this phenomenology by examining the information decomposition of neural signals during such states. Because this approach takes phenomenological evidence as a starting point, we refer to it as the “a posteriori” Ψ ID approach.

An alternative approach to relate phenomenology and Φ ID atoms is to try to identify what each atom may correspond to, in terms of subjective experience, based on what the atoms capture in terms of information processing. This may lead to predictions about how phenomenology should change if the atom in question were manipulated. Such predictions may then be tested empirically by studying perturbations that have been shown to alter the atomic composition (which may be discovered through the first (a posteriori) avenue described above). Because it starts from abstract considerations in terms of information processing, we refer to this avenue as the “a priori” approach of Ψ ID.

Empirical predictions: Φ enomenology

In the following sections, we outline how the theoretical framework of Ψ ID proposed here could function in practice, by conjecturing specific equivalences between Φ ID atoms and various aspects of phenomenology and other psychological phenomena. These provisional predictions are empirically testable using current neuroimaging techniques, and illustrate the practical value of Ψ ID.

At this point, it is worth recapitulating the extent and structure of our theoretical commitments. A fundamental assumption of this work is that it is theoretically possible and meaningful to quantify subjective experience (consciousness) in terms of integrated information of some (suitably chosen) neural dynamics. Subsequent to this background assumption, the core of our contribution is the hypothesis that it may be possible to obtain further insight into subjective experiences in terms of individual information-theoretic atoms, based on the Φ ID framework.

Me, Myself, and Φ : Self and Persistent Synergies

A fundamental aspect of phenomenology that may be understood in terms of Ψ ID is selfhood. Specifically, we propose that a system may constitute an individuated “self” to the extent that its dynamics allow a persistent macroscale description of the system that is causally decoupled (as described in the Section *A deepness in the Φ : Quantifying causal emergence*) from its individual constituent parts - here understood as the microscale. In other words, we posit that a self is associated with neural dynamics in which the macroscale has a causal influence on its own dynamics, beyond what is explainable from the individual microscale components. As discussed in *A deepness in the Φ : Quantifying causal emergence*, this notion corresponds to the presence of persistent synergies in the system, i.e. the Φ ID atom of causal decoupling

(Figures 2 and 3). Note that these underlying intuitions are aligned with those of other recent works that conceptualise selfhood in information-theoretic terms (Chang et al., 2020; Krakauer et al., 2020), although these works use mathematical frameworks that do not enjoy the expressive richness of Φ ID (indeed, extension of these works with the Φ ID framework would be an exciting avenue for future work).

Seen from this perspective, Hume’s account of a “bundle of perceptions” (*Treatise of Human Nature*, Sect. VI. Of Personality, 1739/1986) ignores one fundamental issue: namely, that the parts together can constitute a whole beyond their sum, and high-order structures can persist even when the parts change - as has been formally demonstrated through Φ ID (Rosas et al., 2020). Thus, our proposition mirrors theories such as IIT, which take the unity of experience as their starting point and explain consciousness in terms of integration of information. Indeed, selfhood and consciousness seem tightly bound together in everyday experience. However, we know that they can be dissociated. Examples of a dissociation between consciousness and sense of self are experienced meditators and people under the influence of psychedelics: in both cases, people often report feeling a reduction in their experienced sense of self without acknowledging a diminution of their overall subjective experience - in fact, quite the opposite (see Deane et al., 2020). On the other hand, the effect of general anaesthesia on sense of self is also a topic of recent interest (Sleigh et al., 2020).

At this point, it is worth distinguishing the notions of *selfhood* from *sense of self*. The former concerns the extent to which a system can be demarcated from its environment and stably exist as an independent entity - the extent to which that system constitutes an individual (Weber & Varela 2002; Thompson 2007). Following Krakauer et al. (2020), we take a system’s selfhood to be a graded property, which is determined by the system’s dynamics (Levin 2019). Accordingly, selfhood pertains to systems at all levels of organisation, from humans to paramecia. In contrast, by sense of self we refer to the extent to which an organism perceives *itself* as having or being a self, which is related to higher-level metacognition (but see Friston (2018) for an alternative suggestion). Therefore, a sense of self requires some degree of selfhood that can be acknowledged by the organism’s (possibly inaccurate) read-out of their own selfhood, whereas it is possible to have selfhood without a sense of self if the corresponding metacognitive abilities are not available. We leave open the question of whether any systems may, despite lacking selfhood, nevertheless come to have a delusional belief in their own selfhood - that is, having a sense of self without selfhood. Though seemingly unlikely and even paradoxical, our framework does not rule this out from a formal standpoint - and indeed, surprising and striking dissociations between belief and reality can be observed e.g. in patients suffering from anosognosia, who can adamantly deny obvious deficits from which they suffer.

Preliminary empirical support for a relationship between selfhood and causal emergence (i.e. persistent synergy in the system) is found in recent work that suggests the brain’s default mode network to be highly synergistic (Luppi et al., 2020a). This association is promising, as the default mode network has been consistently implicated in self-referential processing (Qiu & Northoff 2011) as well as the sense of self or “ego” (Carhart-Harris & Friston 2010), and its integrity is compromised during LSD-induced “ego dissolution” (Nour et al., 2016). Furthermore, this network is also implicated in loss of consciousness, whether induced by anaesthesia or severe brain injury (Luppi et al 2019; Vanhaudenhuis et al., 2010; Boveroux et al., 2010; DiPerri et al. 2017; Luppi et al., 2020b). Thus, the DMN may constitute a nexus for the confluence of synergy, consciousness and selfhood in the human brain.

An important implication of identifying selfhood with the Φ ID atoms that correspond to causal decoupling, is that all systems that have selfhood would also be conscious - since causal decoupling atoms are among the consciousness-related atoms that compose Φ_R . However, and perhaps surprisingly, the converse is not the case: transfer-only systems may be conscious despite having no selfhood, according to our proposed framework (see Figure 6). This observation highlights the information-theoretic source of another kind of objection levelled against IIT, based on an intuitive resistance to the notion of certain systems (namely, transfer-only systems) being conscious. In effect, most of the counter-examples of synthetic systems with high Φ and arguably no consciousness display only transfer and no synergy (Oizumi et al., 2014). Fortunately, decomposing Φ into its Φ ID atoms allow us to refine the usage of this metric, giving the practitioner the power to decide whether transfer should be considered part of Φ (much like the subtraction of redundancy was excluded from Φ_R based on theoretical considerations about a metric of consciousness being non-negative). Thus, rather than using counterintuitive examples to reject the theory as a whole, we argue for refining the theory without throwing the baby out with the bathwater, by capitalising on the finer-grained understanding made possible by Φ ID.

Figure 6. Visual representation of our hypothesised relationship between total information (large blue circle), consciousness (Φ_R , medium purple circle) and selfhood (causal decoupling, violet small circle).

Indeed, following the account of individuality and sense of self put forth by Ψ ID, one can posit that the “self-less consciousness” reportedly experienced by advanced meditators, and the ego-dissolution induced by serotonergic psychedelics such as LSD and psilocybin (Carhart-Harris & Friston 2019), may both be the result of a reduction in the causal decoupling (Figure 2) in the composition of their Φ_R , corresponding to a state of consciousness with relatively reduced selfhood. These conjectures could be readily tested on M/EEG or fMRI data.

651 Zones of Thought

652 One intriguing implication of the Ψ ID framework is that different environments may be
 653 conducive to the emergence of alternative modes of consciousness - just as they may be
 654 differently conducive to various forms of life. Most organisms harvest information about their
 655 environment through multiple sensory modalities. The various senses of these organisms often
 656 provide information that is, at least partly, about the same external stimuli. For example, the
 657 same event is often the cause of stimuli delivered by more than one modality, such as
 658 someone's words being conveyed by their lip movements as well as their speech. This suggests
 659 that an environment where events tend to provide complementary information across sensory
 660 modalities, can favour the presence of integration *via* synergy, and organisms that are able to
 661 exploit this property will likely find themselves at an advantage.

662 As an example, in a forest a red, but not green round fruit is edible, but only when it smells
 663 sweet, so that edible exemplars are identifiable only when the two senses are combined. Such
 664 an environment may be expected to favour informational synergy between smell and sight in
 665 animals that rely on this fruit for nourishment. Conversely, animals whose main source of
 666 sustenance is easily identified by a single property (e.g. a specific color or smell) may not
 667 benefit from synergy to the same degree. Thus, the neural architectures of different organisms
 668 may rely on different combinations of information-theoretic atoms, possibly shaped by their
 669 environment and evolutionary history - as suggested by recent empirical evidence
 670 demonstrating that human brains rely on synergy to a greater extent than macaque brains
 671 (Luppi et.al. 2020a).

672 If, as we have argued, selfhood corresponds to causal decoupling (i.e. persistent synergies in
 673 the system), then environments that favour or discourage synergy may have an effect on
 674 selfhood (and presumably also sense of self). This prediction could be tested by means of
 675 virtual reality devices, which could be used to provide participants with visual, auditory, and
 676 tactile stimuli whose contents are entirely unrelated (i.e. stimuli that provide no synergy), and
 677 subsequently probe whether alterations have occurred in their sense of self, and also in the
 678 prevalence of Φ ID atoms corresponding to causal decoupling in their neural dynamics, as
 679 measured e.g. with functional MRI or other neuroimaging modality. Intriguingly, a multi-user
 680 VR platform was recently found to produce 'ego dissolution' type experiences not
 681 incomparable to those produced by moderate doses of psychedelics (Glowacki et al., 2020).

682 Furthermore, as synergy derives from the advantage of combining different sensory sources,
 683 our theory predicts a degradation of selfhood as the unifying factor (and, presumably, the
 684 organism's perception of its own selfhood, i.e. its sense of self) when there is a reduced benefit
 685 of integration between different sources of sensory information. In addition to modifying the
 686 structure of the environment, as proposed above, another way to reach a similar condition
 687 would be to add independent noise in each sensory modality. Doing so would result in a
 688 reduction of signal-to-noise ratio and, hence, a reduction in the proportion of information that
 689 each sensory source can contribute towards synergy. Intriguingly, such a reduction in signal-
 690 to-noise ratio may be part of the mechanism by which LSD induces its well-known ego-
 691 dissolving effects - complementary of effects taking place in top-down activity (e.g., Carhart-
 692 Harris & Friston 2019). In effect, the 5-HT-2A agonistic properties of LSD lead to dysregulated
 693 spontaneous neuronal activity (Nutt et.al. 2020), which may be expected to weaken the

contingency between neuronal firing and external stimuli, hence introducing noise in each channel and reducing the ability of different sensory sources to provide synergistic information - corresponding to reduced causal decoupling, our proposed information-theoretic substrate for selfhood.

The converse of these hypotheses suggests that providing stimulation across different sensory modalities that allows for high synergy may reduce the extent of psychedelic-induced ego-dissolution. Partial support to this hypothesis is provided by recent studies on the effect of different stimuli under LSD, which suggest a competition between the psychedelic effect of the drug and stimulus (Mediano et al., 2020). We predict that by increasing the synergy between different sensory sources through concurrent stimulation of multiple sensory modalities, one might reinforce the self-other boundary - and the subjective evaluation of it - resulting in diminished ego-dissolution.

Discussion

We have provided theoretical contributions about the nature of consciousness (understood as integrated information) based on its decomposition into elementary information-theoretic atoms, and the key insight that the same total integrated information may be comprised of different combinations of information atoms. This approach has allowed us to provide empirical predictions that could be tested with the tools of contemporary neuroscience. A schematic summary of our contributions, and the underlying assumptions, is provided in Figure 7.

Figure 7. Visual summary of Ψ ID, illustrating the logical structure between the various claims made in this paper.

To inΦnity and beyond

The main premise of this piece - and of Ψ ID more broadly - is that there is merit to the principle of quantifying consciousness via integrated information (suitably defined). We acknowledge that the predictions of Ψ ID outlined here are broad and high-level (Figure 7); however, we believe that it is important for a theoretical account to be clear about its empirical commitments. Indeed, we have made predictions in a broad range of areas - many of which could already be tested. In fact, while there is still work to be done on finding the right temporal and spatial scale at which neural information should be best assessed, it is already possible to approach this quantification with effective results (see e.g. Luppi et al., 2020b).

Importantly, the advantages of a Φ ID-based account of consciousness are not restricted to IIT, but rather this framework represents a general lens through which to understand consciousness. Indeed, the presented framework also provides insights about other theoretical approaches to consciousness, such as the Global Neuronal Workspace Theory (Dehaene & Changeux 2011; Mashour et al., 2020). In effect, by re-thinking information exchange in the human brain in terms of synergy and redundancy, it is possible to delineate a “synergistic global workspace” purely from functional considerations - based on brain regions whose connections are predominantly synergistic (Luppi et al 2020b). Furthermore, analysis of resting-state functional MRI data showed that loss of consciousness due to anaesthesia or brain injury corresponds to

a reduction of Φ_R between regions of the synergistic workspace. In this way, the more nuanced view on neural information processes offered by Φ ID brings us closer to reconciling IIT's and GNWT's accounts of consciousness, and offers the promise of further insights for our understanding of consciousness.

Another intriguing future research direction is to explore the relationship between the elaboration of Ψ ID explored herein and hierarchical predictive coding and the Free Energy Principle (FEP) (see Seth & Hohwy 2020). Interestingly, ideas in this direction have been put forward by Friston and colleagues in the context of IIT (Friston et al., 2020), where they suggest that - at least in terms of numerical analyses - the minimization of variational free-energy (which, according to the FEP, is a basic imperative for any self-maintaining cognitive system) *maximizes* Φ and vice versa (Friston et al., 2020). Thus, an exciting question for future research is to assess how the notion of free-energy minimising agents that also maximise Φ , relates to our theoretical contributions put forward above: does maximisation of Φ also correspond to maximisation of Φ_R , and how is it reflected in the Φ_R -ing rate? Is it driven by any specific Φ ID atoms - such as synergy or transfer? Additionally, one could ask about the relationship between downward causation, discussed throughout our paper, to predictive mechanisms in a control hierarchy; specifically, where a higher-level component predicts some general feature of lower-level constituents. We thus believe there are promising overlaps between our account of Ψ ID and the theoretical ambitions of predictive coding and FEP approaches, which deserve to be explored in the future.

So long, and thanks for all the Φ s

The distinction of different Φ ID atoms within integrated information leads to a new understanding of the space of possible consciousness, providing a phenomenological understanding of information-theoretic atoms: we call this framework Ψ ID. This framework provides not only a revised measure of integrated information, Φ_R , but also a way to measure the efficiency of a system at turning information into consciousness - i.e. its " Φ_R -ing rate". Importantly, when combined with a mathematical framework for the definition of causal emergence, Ψ ID enables us to propose a formal solution to the long-standing question of whether consciousness is an emergent phenomenon: namely, we show that both consciousness (understood as integrated information, Φ_R) and emergence each comprise distinct sets of information-theoretic atoms, and only some of them overlap.

Thus, whether consciousness is emergent or not will depend on its information-theoretic composition. Moreover, since Φ_R is composed of different atoms, different systems may achieve the same amount of integrated information through different combinations of information-theoretic atoms. By investigating the phenomenology associated with specific atoms, these "modes of consciousness" may provide a way to eventually understand the phenomenology of different states of consciousness that are not immediately accessible.

In addition to these theoretical contributions for a more nuanced understanding of consciousness, our Ψ ID framework also provides empirically testable predictions. In particular, we have hypothesised that Φ ID atoms involving synergy may correspond to modes of being conscious that involve a sense of self. We look forward to empirical tests of these predictions, and the possible extension of our work to other mental phenomena, such as psychiatric conditions.

Acknowledgements

The authors are grateful to Marta Halina and members of her research group for helpful discussions. The authors would also like to acknowledge the intellectual influence of Dr. Vernor Vinge, whose vision helped to shape the context of this work - especially as laid out in the Zones of Thought series: *A Fire upon the Deep*, and *A Deepness in the Sky*. The authors believe that the influence of works of science fiction in shaping scientific inquiry is insufficiently acknowledged in the scientific literature, and wish to contribute to redress this state of affairs.

This work was supported by the Gates Cambridge Trust (to AIL); the Stephen Erskine Fellowship (Queens' College, Cambridge, to EAS); the Wellcome Trust (grant no. 210920/Z/18/Z; to PAM and DB); The History and Philosophy of Science Trust Fund (to DJH); and the Ad Astra Chandaria foundation (to FR); Ad Astra Trust, Tim Ferriss, The Nikean Foundation, and The Tamas Family (to (RLC-H).

Data availability

Code to perform Integrated Information Decomposition is available upon request from author PAM: email pam83@cam.ac.uk.

References

- Atasoy, S., Roseman, L., Kaelen, M., Kringelbach, M.L., Deco, G., & Carhart-Harris, R.L. 2017. Connectome-harmonic decomposition of human brain activity reveals dynamical repertoire re-organization under LSD. *Scientific Reports*, vol.7: 17661. <https://doi.org/10.1038/s41598-017-17546-0>
- Atasoy, S., Vohryzek, J., Deco, G., Carhart-Harris, R.L., & Kringelbach, M.L. 2018. Common neural signatures of psychedelics: Frequency-specific energy changes and repertoire expansion revealed using connectome-harmonic decomposition. *Progress in Brain Research*, vol. 242: 97-120. <https://doi.org/10.1016/bs.pbr.2018.08.009>
- Balduzzi, D. & Tononi, G. 2008. Integrated Information in Discrete Dynamical Systems: Motivation and Theoretical Framework. *PLoS Computational Biology*, doi: <https://doi.org/10.1371/journal.pcbi.1000091>

808 Balduzzi, D. & Tononi, G. 2009. Qualia: The Geometry of Integrated Information. *PLoS*
809 *Computational Biology*, vol. 5(8): e1000462.
810 <https://doi.org/10.1371/journal.pcbi.1000462>

811 Barrett, A.B. 2014. An integration of integrated information theory with fundamental physics.
812 *Frontiers in Psychology*, vol.5 (63). DOI: <https://doi.org/10.3389/fpsyg.2014.00063>

813 Barrett, A.B. & Seth A.K. 2011. Practical measures of integrated information for time series
814 data. *PLoS Computational Biology*, vol.7, e1001052. DOI:
815 [10.1371/journal.pcbi.1001052](https://doi.org/10.1371/journal.pcbi.1001052)

816 Barttfeld, P., Uhrig, L., Stitt, J., Sigman, M., Jarraya, B., and Dehaene, S. 2015. Signature of
817 consciousness in the dynamics of resting-state brain activity. *Proceedings of the National*
818 *Academy of Sciences*, vol. 112(3): 887-892. doi.org/10.1073/pnas.1418031112

819 Bedau, M.A. 1997. Weak emergence. *Philosophical perspectives*, vol.11: 375-399. DOI:
820 [10.1111/0029-4624.31.s11.17](https://doi.org/10.1111/0029-4624.31.s11.17)

821 Bedau, M.A., 2002. Downward causation and the autonomy of weak emergence. *Principia: An*
822 *international journal of epistemology*, vol.6(1): 5-50. DOI:
823 [10.7551/mitpress/9780262026215.003.0010](https://doi.org/10.7551/mitpress/9780262026215.003.0010)

824 Bertschinger, N., Rauh, J., Olbrich, E., Jost, J. & Ay, N. 2014. “Quantifying Unique
825 Information.” *Entropy*, vol. 16 (4): 2161–2183. DOI: <https://doi.org/10.3390/e16042161>

826 Boveroux, P., Vanhaudenhuyse, A., Bruno, M.A., Noirhomme, Q., Lauwick, S., Luxen, A.,
827 Degueldre, C., Plenevaux, A., Schnakers, C., Phillops, C., Brichant, J.F., Bonhomme,
828 V., Maquet, C., Greicius, M.D., Laureys, S., & Boly, M. 2010. Breakdown of within-
829 and between-network resting state functional magnetic resonance imaging connectivity

830 during propofol-induced loss of consciousness. *Anesthesiology*, vol. 113(5): 1038-53.
831 DOI: <http://doi.org/10.1097/ALN.0b013e3181f697f5>

832 Breakspear, M., Williams, L.M. & Stam, C.J. 2004. A novel method for the topographic
833 analysis of neural activity reveals formation and dissolution of dynamic cell assemblies.
834 *Journal of Computational Neuroscience*, vol.16(1): 49-69. DOI:
835 <https://doi.org/10.1023/B:JCNS.00000004841.66897.7d>

836 Cai, L., Wang, J., Guo, Y., Lu, M., Dong, Y., Wei, X. 2020. Altered inter-frequency dynamics
837 of brain networks in disorders of consciousness. *Journal of Neural Engineering*, vol.
838 17(3): 036006.

839 Cao, Y., Summerfield, C., Park, H., Giordana, B.L., & Kayser, C. 2019. Causal Inference in
840 the Multisensory Brain. *Neuron*, vol.102: 1076-1087. DOI:
841 <https://doi.org/10.1016/j.neuron.2019.03.043>

842 Carhart-Harris, R.L. & Friston, K. 2010. The default-mode, ego-functions and free-energy: a
843 neurobiological account of Freudian ideas. *Brain: A Journal of Neurology*, vol.133(4):
844 1265-1283. DOI: <https://doi.org/10.1093/brain/awq010>

845 Carhart-Harris, R.L. & Friston, K. 2019. REBUS and the Anarchic Brain: Toward a Unified
846 Model of the Brain Action of Psychedelics. *Pharmacological Reviews*, vol.71(3): 316-
847 344. DOI: <https://doi.org/10.1124/pr.118.017160>

848 Casali, A.G., Gosseries, O., Rosanova, M., Boly, M., Sarasso, S., Casali, K.R., Casarotto, S.,
849 Bruno, M.A., Laureys, S., Tononi, G., & Massimini, M.A. 2013. Theoretically Based
850 Index of Consciousness Independent of Sensory Processing and Behavior. *Science*
851 *Translational Medicine*, vol. 5(198): 198ra105. DOI: 10.1126/scitranslmed.3006294

852 Cavanna, F., Vilas, M.G., Palmucci, M. & Tagliazucchi, E. 2018. Dynamic Functional
 853 Connectivity and Brain Metastability during Altered States of Consciousness.
 854 *NeuroImage*, vol. 180: 383–395. DOI: <http://doi.org/10.1016/j.neuroimage.2017.09.065>.

855 Cea, I. 2020. Integrated Information Theory of Consciousness is a Functionalist Emergentism.
 856 *Synthese*, DOI: <https://doi.org/10.1007/s11229-020-02878-8>

857 Chang, A.Y.C., Biehl, M., Yu, Y. & Kanai, R. 2020. Information Closure Theory of
 858 Consciousness. *Frontiers in Psychology*, DOI:
 859 <https://doi.org/10.3389/fpsyg.2020.01504>

860 Colombetto, G. & Ratcliffe, M. 2012. Bodily Feeling in Depersonalization: A
 861 Phenomenological Account. *Emotion Review*, vol.4(2):
 862 <https://doi.org/10.1177/1754073911430131>

863 Crick, F. & Koch, C. 2003. A framework for consciousness. *Nature Neuroscience*, vol.6: 119-
 864 126. DOI: <https://doi.org/10.1038/nm0203-119>

865 Deane, G. 2020. Dissolving the self: Active inference, psychedelics, and ego-dissolution.
 866 *Philosophy and the Mind Sciences*, vol. 1(1):
 867 <https://doi.org/10.33735/phimisci.2020.I.39>

868 Deane, G., Miller, M. & Wilkinson, S. 2020. Losing Ourselves: Active Inference,
 869 Depersonalization, and Meditation. *Frontiers in Psychology*, 11:539726. Doi:
 870 <https://doi.org/10.3389/fpsyg.2020.539726>

871 De Caro, M. & Grasso, M. 2017. Three Views on Mental Downward Causation. In Paoletti,
 872 M.P. & Orilla, F. *Philosophical and Scientific Perspectives on Downward Causation*,
 873 New York: Routledge.

874 Deco, G., Cruzat, J., Cabral, J., Tagliazucchi, E., Laufs, H., Logothetis, N.K., & Kringelbach,
875 M.L. 2019. Awakening: Predicting external stimulation to force transitions between
876 different brain states. *Proceedings of the National Academy of Sciences*, vol. 116(36):
877 18088-18097. <https://doi.org/10.1073/pnas.1905534116>

878 Dehaene, S. & Changeuz, J.P. 2011. Experimental and Theoretical Approaches to Conscious
879 Processing. *Neuron*, vol. 70(2): 200-227. Doi:
880 <https://doi.org/10.1016/j.neuron.2011.03.018>

881 Demertzi, A., Tagliazucchi, E., Dehaene, S. ... & Stitt, J.D. 2019. Human consciousness is
882 supported by dynamic complex patterns of brain signal coordination. *Science Advances*
883 *Research Article*, vol. 5: eaat7603. DOI: [10.1126/sciadv.aat7603](https://doi.org/10.1126/sciadv.aat7603)

884 Dinesh, P., Li, D., Dean, J.G., Brito, M., Liu, T., Fryzel, A.M., Hudetz, A.G., & Mashour, G.A.
885 2020. Level of Consciousness is Dissociable from Electroencephalographic Measures of
886 Cortical Connectivity, Slow Oscillations, and Complexity. *Journal of Neuroscience*,
887 vol.40(3): 605-618. DOI: <https://doi.org/10.1523/JNEUROSCI.1910-19.2019>

888 Di Perri, C., Amico, E., Heine, L., Annen, J., Martial, C., Larroque, S.K., Soddu, A.,
889 Marinazzo, D., & Laureys, S. 2017. Multifaceted Brain Networks Reconfiguration in
890 Disorders of Consciousness Uncovered by Co-Activation Patterns. *Human Brain*
891 *Mapping*, vol.39(1): 89-103. DOI: <https://doi.org/10.1002/hbm.23826>

892 Egelman, S., Chander, D., Reynolds, C., Ouellette, N.T., & MacIver, M.B. 2019. Nonlinear
893 dynamics captures brain states at different levels of consciousness in patients
894 anesthetized with propofol. *PLOS One*, vol. 14(10): e0223921.
895 <https://doi.org/10.1371/journal.pone.0223921>

896 Feder, M. & Merhav, N. 1994. Relations between entropy and error probability. *IEEE*
897 *Transactions on Information Theory*, vol.40(1): 259-266. DOI: 10.1109/18.272494

898 Feinberg, T.E. & Mallot, J. 2020. Phenomenal Consciousness and Emergence: Eliminating the
899 Explanatory Gap. *Frontiers in Psychology*, 11:1041. Doi:
900 <https://doi.org/10.3389/fpsyg.2020.01041>

901 Friston, K. 2012. A Free Energy Principle for Biological Systems. *Entropy*, vol. 14(11): 2100-
902 2121. DOI: <https://doi.org/10.3390/e14112100>

903 Friston, K. 2018. Am I Self-Conscious? (Or Does Self-Organization Entail Self-
904 Consciousness?). *Frontiers in Psychology*, vol.9. DOI:
905 <https://doi.org/10.3389/fpsyg.2018.00579>

906 Friston, K., Sengupta, B. & Auletta, G. 2014. Cognitive Dynamics: From Attractors to Active
907 Inference. *Proceedings of the IEEE*, vol. 102 (4): 427–445., doi:
908 <https://doi.org/10.1109/jproc.2014.2306251>

909 Friston, K.J., Wiese, W., & Hobson, A.J. 2020. Sentience and the Origins of Consciousness:
910 From Cartesian Duality to Markovian Monism. *Entropy*, vol.22(5), 516. DOI:
911 <https://doi.org/10.3390/e22050516>

912 Glowacki, D.R., Wonnacott, M.D., Freire, R., Glowacki, B.R., Gale, E.M., Pike, J.E., de Haan,
913 T., Chatziapostolou, M. & Metlata, O. 2020. Isness: Using Multi-Person VR to Design
914 Peak Mystical Type Experiences Comparable to Psychedelics. *CHI 20: Proceedings of*
915 *the 2020 CHI Conference on Human Factors in Computing Systems*, 1-14. DOI:
916 <https://doi.org/10.1145/3313831.3376649>

917 Griffith, V., & Koch, C. 2014. “Quantifying Synergistic Mutual Information.” *Guided Self-*
918 *Organization: Inception Emergence, Complexity and Computation*: 159–190. doi:
919 https://doi.org/10.1007/978-3-642-53734-9_6

920 Hain, G., Zamora-Lopez, G., Uhrig, L., Tagliazucchi, E., Laufs, H., Mantini, D., Kringelbach,
921 M., Jarraya, B., Deco, G. 2021. Signature of consciousness in brain-wide
922 synchronization patterns of monkey and human fMRI signals. *NeuroImage*, vol. 226:
923 117470.
924 <https://doi.org/10.1016/j.neuroimage.2020.117470>

925 Hellman, M. & Raviv, J. 1970. Probability of error, equivocation, and the Chernoff bound.
926 *IEEE Transactions on Information Theory*, vol.16(4): 368-372. DOI:
927 <https://doi.org/10.1109/TIT.1970.1054466>

928 Hesp, C., Smith, R., Parr, T., Allen, M., Friston, K. & Ramstead, M. 2019. Deeply Felt Affect:
929 The Emergence of Valence in Deep Active Inference. *PsyArXiv Preprints*, DOI:
930 [10.31234/osf.io/62pfd](https://doi.org/10.31234/osf.io/62pfd)

931 Huang, Z., Zhang, J., Wu, J., Mashour, G.A., Hudetz, A.G. 2020. Temporal circuit of
932 macroscale dynamic brain activity supports human consciousness. *Science Advances*,
933 vol.6(11): eaaz0087. DOI: 10.1126/sciadv.aaz0087

934 Hume, D. 1986. *A Treatise of Human Nature: Being an Attempt to Introduce the Experimental*
935 *Method of Reasoning*. London: Penguin Classics.

936 Hutchinson, R.M., Hutchinson, M., Manning, K.Y., Menon, R.S., & Everling S. 2014. Isolurane
937 induces dose-dependent alterations in the cortical connectivity profiles and dynamic
938 properties of the brain’s functional architecture. *Human Brain Mapping*, vol.35(12):

939 5754-75.
 940 doi:10.1002/hbm.22583.

941 James R.G., Ellison, C., & Crutchfield, J. 2011. Anatomy of a bit: Information in a time series
 942 observation. *Chaos: An Interdisciplinary Journal of Nonlinear Science*, vol. 21(3).
 943 <https://doi.org/10.1063/1.3637494>

944 James, R.G. & Crutchfield, J.P. 2017. Multivariate Dependence Beyond Shannon Information.
 945 *Entropy*, vol.19(10), 531. <https://doi.org/10.3390/e19100531>

946 Jaynes, T. 2003. *Probability Theory: The Logic of Science*. Cambridge: Cambridge University
 947 Press.

948 Kleiner, J. 2020. Mathematical Models of Consciousness. *Entropy*, 22(6). DOI:
 949 <https://doi.org/10.3390/e22060609>

950 Krakauer, D., Bertschinger, N., Olbrich, E., Flack, J.C. & Ay, N. 2020. The information theory
 951 of individuality. *Theory in Biosciences*, vol.139: 209-223. DOI:
 952 <https://doi.org/10.1007/s12064-020-00313-7>

953 Lee., H., Golkowski, D., Jordan, D., Berger, S., Ilg, R., Lee, J. Mashour, G.A., & Lee, U. 2019.
 954 Relationship of critical dynamics, functional connectivity, and states of consciousness in
 955 large-scale human brain networks. *Neuroimage*, vol.188: 228-238. DOI:
 956 <https://doi.org/10.1016/j.neuroimage.2018.12.011>

957 Levin, M. 2019. The Computational Boundary of a “Self”: Developmental Bioelectricity
 958 Drives Multicellularity and Scale-Free Cognition. *Frontiers in Psychology*, DOI:
 959 <https://doi.org/10.3389/fpsyg.2019.02688>

960 Lord L.D., Expert, P., Atasoy, S., Roseman, L., Rapuano, K., Lambiotte, R., Nutt, D.J., Deco,
 961 G., Carhart-Harris, R.L., Kringelbach, M.L., Cabral, J. 2019. Dynamical exploration of
 962 the repertoire of brain networks at rest is modulated by psilocybin. *NeuroImage*, vol.199:
 963 127-142. DOI: <https://doi.org/10.1016/j.neuroimage.2019.05.060>

964 Liuzzi, L., Gascoyne, L.E., Tewarie, P.K., Barratt, E.L., Boto, E., & Brookes, M.J. 2017.
 965 Optimising Experimental Design for MEG Resting State Functional Connectivity
 966 Measurement. *NeuroImage*, vol.155: 565–576. DOI:
 967 <https://doi.org/10.1016/j.neuroimage.2016.11.064>.

968 Lizier, J., Bertschinger, N., Jost, J., & Wibral, M. 2018. “Information Decomposition of Target
 969 Effects from Multi-Source Interactions: Perspectives on Previous, Current and Future
 970 Work.” *Entropy*, vol. 20(4): 307. <https://doi.org/10.3390/e20040307>

971 Luppi, A., Craig, M., Pappas, I., Finoia, P., Williams, G.B., Allanson, J., Pickard, J.D., Owen,
 972 A.M., Naci, L., Menon, D.K., & Stamatakis, E.A. 2019. Consciousness-specific dynamic
 973 interactions of brain integration and functional diversity. *Nature Communications*,
 974 vol.10: 1-12. <https://doi.org/10.1038/s41467-019-12658-9>

975 Luppi, A., Mediano, P.A.M., Rosas, F.E., Holland, N., Fryer, T.D., O’Brien, J.T., Rowe, J.B.,
 976 Menon, D.K., Bor, D., & Stamatakis, E.A. 2020a. A synergistic core for human brain
 977 evolution and cognition. *bioRxiv preprints*, DOI:
 978 <https://doi.org/10.1101/2020.09.22.308981>

979 Luppi, A., Mediano, P.A.M., Rosas, F.E., Allanson, J., Pickard, J.D., Carhart-Harris, R.L.,
 980 Williams, G.B., Craig, M.M., Finoia, P., Owen, A.M., Naci, L., Menon, D.K., Bor, D.,
 981 & Stamatakis, E.A. 2020b. A Synergistic Workspace for Human Consciousness

982 Revealed by Integrated Information Decomposition. *bioRxiv preprints*, DOI:
983 <https://doi.org/10.1101/2020.11.25.398081>

984 Luppi, A., Vohryzek, J., Kringelbach, M.L., Mediano, P.A.M., Craig, M.M., Adapa, R.,
985 Carhart-Harris, R.L., Roseman, L., Pappas, I., Finoia, P., Williams, G.B., Allanson, J.,
986 Pickard, J.D., Menon, D.K., Atasoy, S., & Stamatakis, E.A 2020c. Connectome
987 Harmonic Decomposition of Human Brain Dynamics Reveals a Landscape of
988 Consciousness.
989 *bioRxiv*: <https://doi.org/10.1101/2020.08.10.244459>

990 Luppi, A., Carhart-Harris, R., Roseman, L., Pappas, I., Menon, D.K., & Stamatakis, E.A.
991 2020d. LSD alters dynamic integration and segregation in the human brain. *Neuroimage*,
992 vol. 227, doi: <https://doi.org/10.1016/j.neuroimage.2020.117653>

993 Mashour, G., Roelfsema, P., Changeux, J.P., & Dehaene, S. 2020. Conscious Processing and
994 the Global Neuronal Workspace Hypothesis. *Neuron*, vol. 105(5): 776-798. DOI:
995 [10.1016/j.neuron.2020.01.026](https://doi.org/10.1016/j.neuron.2020.01.026)

996 Mediano, P., Seth, A.K., & Barrett, A.B. 2018. Measuring Integrated Information:
997 Comparison of Candidate Measures in Theory and Simulation. *Entropy*, vol.21(1), 17.
998 DOI: <https://doi.org/10.3390/e21010017>

999 Mediano, P., Rosas, F., Carhart-Harris, R.L., Seth, A.K., & Barrett, A. 2019. Beyond integrated
1000 information: A taxonomy of information dynamics phenomena. *Neurons and Cognition*.
1001 Available from [arXiv:1909.02297](https://arxiv.org/abs/1909.02297)

1002 Mediano, P.A.M., Rosas, F.E., Timmerman, C., Roseman, L., Nutt, D.J., Fielding, A., Kaelen,
1003 M., Kringelbach, M.L., Barrett, A.B., Seth, A.K., Muthukumaraswamy, S., Bor, D. &

1004 Carhart-Harris, R.L. 2020. Effects of external stimulation on psychedelic state
1005 neurodynamics. *bioRxiv preprints*, DOI: <https://doi.org/10.1101/2020.11.01.356071>

1006 Moon, K. & Pae, H. 2019. Making Sense of Consciousness as Integrated Information –
1007 Evolution and Issues of Integrated Information Theory. *The Journal of Cognitive*
1008 *Psychology*, vol. 20(1): 1-52.

1009 Nagel, T. 1974. What Is It Like to Be a Bat? *The Philosophical Review*, vol.83(4): 435-450.
1010 <https://doi.org/10.2307/2183914>

1011 Northoff, G., Wainio-Theberge, S. & Evers, K. 2020. Is Temporo-Spatial Dynamics the
1012 ‘Common Currency’ of Brain and Mind? In Quest of ‘Spatiotemporal Neuroscience.
1013 *Physics of Life Reviews*, vol. 33: 34–54. DOI:
1014 <https://doi.org/10.1016/j.plrev.2019.05.002>

1015 Nour, M.M., Evans, L., Nutt, D., & Carhart-Harris, R.L. 2016. Ego-Dissolution and
1016 Psychedelics: Validation of the Ego-Dissolution Inventory (EDI). *Frontiers in Human*
1017 *Neuroscience*, DOI: <https://doi.org/10.3389/fnhum.2016.00269>

1018 Nutt, D., Erritzoe, D. & Carhart-Harris, R.L. 2020. Psychedelic Psychiatry’s Brave New
1019 World. *Cell Commentary*, vol.181(1): 24-28. DOI:
1020 <https://doi.org/10.1016/j.cell.2020.03.020>

1021 O’neill, G.C., Tewarie, P., Vidaurre, D., Liuzzi, L., Wollrich, M.W., Brookes, M.J. 2018.
1022 Dynamics of Large-Scale Electrophysiological Networks: A Technical Review.
1023 *NeuroImage*, vol.180: 559–576. DOI: <https://doi.org/10.1016/j.neuroimage.2017.10.003>

1024 Oizumi, M., Albantakis, L., Tononi, G. 2014. From the Phenomenology to the Mechanisms of
1025 Consciousness: Integrated Information Theory 3.0. *PLoS Computational Biology*,
1026 vol.10(5). DOI: <https://doi.org/10.1371/journal.pcbi.1003588>

1027 Oizumi, M., Tsuchiya, N. & Amari, S. 2016. Unified Framework for Information Integration
1028 Based on Information Geometry. *Proceedings of the National Academy of Sciences*, vol.
1029 113(51): 14817–14822. DOI: <https://doi.org/10.1073/pnas.1603583113>.

1030 Palacios, E.R., Razi, A., Parr, T., Kirchhoff, M., & Friston, K. 2017. Biological Self-
1031 Organisation and Markov Blankets. *bioRxiv*, doi: <https://doi.org/10.1101/227181>

1032 Palacios, E.R., Isomura, T., Parr, T. & Friston, K. 2019. The Emergence of Synchrony in
1033 Networks of Mutually Inferring Neurons. *Scientific Reports*, vol. 9(1). DOI:
1034 <https://doi.org/10.1038/s41598-019-42821-7>

1035 Parr, T. & Friston, K. 2018. Generalised Free Energy and Active Inference: Can the Future
1036 Cause the Past? *Biological Cybernetics*, vol. 113: 495-513. DOI:
1037 <https://doi.org/10.1007/s00422-019-00805-w>

1038 Parrondo, J.M.R., Horowitz, J.M., & Sagawa, T. 2015. Thermodynamics of information.
1039 *Nature Physics* 11: 131-139. DOI: <https://doi.org/10.1038/nphys3230>

1040 Rosas F., Ntranos, V., Ellison, C.J., Pollin, S., & Verhelst, M. 2016. Understanding
1041 Interdependency Through Complex Information Sharing. *Entropy*, vol.18(2), 38:
1042 <https://doi.org/10.3390/e18020038>

1043 Rosas, F.E., Mediano, Pedro, A.M., Jensen, J.H., Seth, A.K., Barrett, A.B., Carhart-Harris,
1044 R.L., Bor, D. 2020. Reconciling emergences: An information-theoretic approach to
1045 identify causal emergence in multivariate data. *arXiv preprint*: arXiv:2004.08220.

- 1046 Schwitzgebel, E. 2016. Phenomenal Consciousness, Defined and Defended as Innocently as I
1047 Can Imagine. *Journal of Consciousness Studies*, vol. 23(11-12): 224-235.
- 1048 Searle, John R. (mills Professor Of Mind And Language, Univ. *Mind - a Brief Introduction*.
1049 Oxford University Press, 2005.
- 1050 Seth, A. & Friston, K. 2016. Active interoceptive inference and the emotional brain.
1051 *Philosophical Transactions of the Royal Society B*, vol. 371(1708):
1052 <https://doi.org/10.1098/rstb.2016.0007>
- 1053 Seth, A.K. & Hohwy, J. 2020. Predictive processing as an empirical theory *for* consciousness
1054 science. *Cognitive Neuroscience Preprints*, DOI: [10.1080/17588928.2020.1838467](https://doi.org/10.1080/17588928.2020.1838467)
- 1055 Shannon, C.E. 1948. A Mathematical Theory of Communication. *The Bell System Technical*
1056 *Journal*, vol.27: 379-423, 623-656. DOI: [https://doi.org/10.1002/j.1538-](https://doi.org/10.1002/j.1538-7305.1948.tb01338.x)
1057 [7305.1948.tb01338.x](https://doi.org/10.1002/j.1538-7305.1948.tb01338.x)
- 1058 Sleight, J., Warnaby, C. & Tracey I. General Anaesthesia as fragmentation of selfhood: insights
1059 from electroencephalography and neuroimaging. *British Journal Anaesthesia*, vol.
1060 121(1): 233-240. Doi: 10.1016/j.bja.2017.12.038
- 1061 Standage, D., Areshenkoff, C.N., Nashed, J.Y., Hutchinson, R.M., Hutchinson, M., Heinke,
1062 D., Menin, R.S., Everling, S., & Gallivan, J.P. 2020. Dynamic Reconfiguration,
1063 Fragmentation, and Integration of Whole-Brain Modular Structure across Depths of
1064 Consciousness. *Cerebral Cortex*, vol. 30(10): 5229-5241.
1065 <https://doi.org/10.1093/cercor/bhaa085>

- 1066 Stramaglia, S., Cortes, J.M., & Marinazzo D. 2014. Synergy and redundancy in the Granger
1067 causal analysis of dynamical networks. *New Journal of Physics*, vol.16(10), 105003:
1068 arXiv:1403.5156
- 1069 Tononi, G. 2004. An information theory of consciousness. *BMC Neuroscience*, vol.5, 42. DOI:
1070 <https://doi.org/10.1186/1471-2202-5-42>
- 1071 Tononi, G. & Koch, C. 2015. Consciousness: here, there, and everywhere? *Philosophical*
1072 *Transactions of the Royal Society, B* 370: 20140167. DOI:
1073 <https://doi.org/10.1098/rstb.2014.0167>
- 1074 Tononi, G., Boly, M., Massimini, M., & Koch, C. 2016. Integrated Information Theory: from
1075 Consciousness to Its Physical Substrate. *Nature Reviews Neuroscience*, vol.17(7): 450–
1076 461. DOI: <https://doi.org/10.1038/nrn.2016.44>
- 1077 Tononi, G., Sporns, O. & Edelman, G. 1994. A measure for brain complexity: relating
1078 functional segregation and integration in the nervous system. *Proc. Natl. Acad. Sci. USA*,
1079 vol.91(11): 5033-7. DOI: 10.1073/pnas.91.11.5033
- 1080 Tononi, G., Sporns, O., & Edelman, G. 1998. Complexity and coherency: integrating
1081 information in the brain. *Trends in Cognitive Science*, vol.2(12): 474-84. DOI:
1082 [10.1016/s1364-6613\(98\)01259-5](https://doi.org/10.1016/s1364-6613(98)01259-5)
- 1083 Tononi, G. & Edelman, G. 1998. Consciousness and Complexity. *Science*, vol. 282(5395):
1084 1856-1851. DOI: 10.1126/science.282.5395.1846
- 1085 Turkheimer, F.E., Rosas, F.E., Dipasquale, O., Martins, D., Fagerholm, E.D., Expert, P., Vasa,
1086 F., Lord, L.D., Leech, R. 2020. A Complex Systems Perspective on Neuroimaging
1087 Studies of Behaviour and Its Disorders. *Complex Systems Perspective on Neuroimaging*

1088 *Studies of Behaviour and its Disorders Preprints.*
 1089 doi:10.20944/preprints202008.0654.v1.

1090 Tsuchiya, N., Taguchi, S., Saigo, H. 2016. Using category theory to assess the relationship
 1091 between consciousness and integrated information theory. *Neuroscience Research*, vol
 1092 107: 1-7. Doi: <https://doi.org/10.1016/j.neures.2015.12.007>

1093 Uhrig, L., Stitt, J.D., Jacob, A., Tasserie, J., Barttfeld, P., Dupont, M., Dehaene, S., Jarraya, B.
 1094 2018. Resting-state Dynamics as a Cortical Signature of Anaesthesia Monkeys.
 1095 *Anesthesiology*, vol, 129(5): 942-958. DOI: [10.1097/ALN.0000000000002336](https://doi.org/10.1097/ALN.0000000000002336)

1096 Wibral, M., Priesemann, V., Kay, J.W., Lizier, J.T., & Philips, W.A. 2017. Partial Information
 1097 Decomposition as a Unified Approach to the Characterization and Design of Neural Goal
 1098 Functions. *BMC Neuroscience*, vol.16(S1). DOI:
 1099 <https://doi.org/10.1016/j.bandc.2015.09.004>

1100 Vanhaudenhuyse, A., Noirhomme, Q., Tshibanda, L.J.-F., Bruno, M.A., Boveroux, P.,
 1101 Schnakers, C., Soddu, A., Perlberg, V., Ledoux, D., Brichant, J.-F., Moonen, G., Maquet,
 1102 P., Greicius, M.D., Laureys, S., & Boly, M. 2010. Default network connectivity reflects
 1103 the level of consciousness in non-communicative brain-damaged patients. *Brain: A*
 1104 *Journal of Neurology*, vol.133(1): 161-171. DOI: <https://doi.org/10.1093/brain/awp313>

1105 Varly, T.F., Denny, V., Sporns, O., & Patania, A. 2020a. Topological Analysis of Differential
 1106 Effects of Ketamine and Propofol Anesthesia on Brain Dynamics. *bioRxiv*,
 1107 doi: <https://doi.org/10.1101/2020.04.04.025437>

1108 Varley, T.F., Luppi, A., Pappas, I., Naci, L., Adapa, R., Owen, A.M., Menon, D.K. &
 1109 Stamatakis, E.A. 2020b. Consciousness & Brain Functional Complexity in Propofol

1110 Anaesthesia. *Scientific Reports*, vol. 10: 1018. DOI: <https://doi.org/10.1038/s41598-020->
1111 [57695-3](https://doi.org/10.1038/s41598-020-57695-3)

1112 Vlisides, P.E., Li, D., Zierau, M., Lapointe, A.P., Ip, K.A., McKinney, A.M., & Mashour, G.A.
1113 2019. Dynamic Cortical Connectivity during General Anesthesia in Surgical Patients.
1114 *Anesthesiology*, vol. 130: 885-897. <https://doi.org/10.1097/ALN.0000000000002677>

1115 Weber, A & Varela, J. 2002. Life after Kant: Natural purposes and the autopoietic foundations
1116 of biological individuality. *Phenomenology and the Cognitive Sciences*, vol.1: 97-125.
1117 DOI: <https://doi.org/10.1023/A:1020368120174>

1118 Williams, P.L. 2011. *Information Dynamics: Its Theory and Application to Embodied*
1119 *Cognitive Systems*. Ph.D. Thesis, Indiana University.

1120 Williams, P.L., & Beer, R.D. 2010. Nonnegative decomposition of multivariate information.
1121 Available from [arXiv:1004.2515](https://arxiv.org/abs/1004.2515).

1122 Zhang, R., Zhang, L., Guo, Y., Shi, L., Gai, J., Wang, X., Hu, Y. 2020. Effects of High-
1123 Definition Transcranial Direct-Current Stimulation on Resting-State Functional
1124 Connectivity in Patients with Disorders of Consciousness. *Frontiers in Human*
1125 *Neuroscience*, vol. 23: 14:560586. doi: 10.3389/fnhum.2020.560586