Tam Hunt

Calculating the Boundaries of Consciousness in General Resonance Theory

Abstract: *When physical structures resonate in proximity to each other they will under certain circumstances 'sync up' in a shared resonance frequency. This is the phenomenon of spontaneous self-organization. General resonance theory (GRT), a theory of consciousness developed by Hunt and Schooler, suggests that consciousness is a product of various shared resonance frequencies at different physical scales. I suggest a heuristic for calculating the boundaries and resulting capacity for phenomenal consciousness in such resonating structures. Shared resonance results in phase transitions in the speed and bandwidth of information exchange and thus richer and more complex consciousness. This approach is a solution to the 'combination problem' and 'boundary problem' of consciousness. The proposed mathematical heuristic is a practical approach for identifying potential conscious structures and the spatial and temporal boundaries of such structures over time, and also for calculating the capacity for phenomenal consciousness of any putative conscious entity. The slowest-frequency shared resonance — the 'slowest common denominator' — is the limiting factor for the spatial extent of any macro-consciousness. Various synchrony indexes are discussed. I describe some limitations of the proposed framework, and how it compares to Tononi's integrated information theory. IIT's constellation-qualia characterization framework is compatible with GRT and may be a useful tool in conjunction with GRT's quantification framework.*

Correspondence:
Tam Hunt, University of California, Santa Barbara, CA 93106, USA.
Email: tam.hunt@gmail.com

1   **1. Introduction**

2   The notion of resonance (sometimes described as synchrony,
3   coherence, or shared vibrations, which are similar but not identical
4   phenomena) has a long history in neuroscience. Crick and Koch
5   featured this concept in their neurobiological theory of consciousness
6   (Crick and Koch, 1990; Koch, 2004). John (2001) makes 'zero phase
7   lag synchronization' central to his electromagnetic field theory of con-
8   sciousness. Varela and colleagues (2001) suggested that the most
9   plausible candidate for large-scale integration of consciousness is the
10   'formation of dynamic links mediated by synchrony'. Fries (2005;
11   2015) has made the concept of 'communication through coherence'
12   (neural synchrony/resonance) even more widely known. Nunez and
13   Srinivasan (2010) have developed a 'binding by resonance' approach
14   in various works; Dehaene (2014) highlights the role of long-range
15   synchrony between cortical areas as a key 'signature of conscious-
16   ness' (as does Koch, 2004). Hahn *et al.* (2014) have developed a
17   'communication through resonance' theory of neuronal network
18   dynamics. Grossberg (2017) has developed an adaptive resonance
19   theory (ART) of consciousness over the last two decades and argues
20   that 'all conscious states are resonant states', but that not all resonant
21   states are conscious states. Bandyopadhyay (2019) has made the con-
22   cept of resonance and resonance chains central to his fractal informa-
23   tion theory of consciousness.

24   This paper provides a new method for calculating the spatial and
25   temporal boundaries, and the consequent capacity for phenomenal
26   consciousness, of any conscious entity in each moment. It builds upon
27   the mathematical framework described in Hunt (2011), which suggested
28   a method for calculating the phenomenal capacity of any conscious
29   entity, but not a method for calculating spatial or temporal boundaries.

30   The proposed methodology is grounded in a panpsychist framework
31   (Hunt, 2011; Schooler, Hunt and Schooler, 2011; Hunt and Schooler,
32   2019; Goff, 2017) that assumes that all matter is associated with at
33   least some capacity for phenomenal consciousness, albeit extremely
34   rudimentary in the vast majority of matter. Accordingly, the general
35   resonance theory (GRT) developed in Hunt and Schooler (2019) and
36   further in the present paper is applicable to all physical structures,
37   rather than being limited only to neurobiological or biological
38   structures.

39   GRT suggests that resonance (similar but not synonymous with
40   synchronization and coherence) of various types is the key mechanism

1   by which the basic constituents of consciousness combine into more
2   complex types of consciousness. This is the case because shared
3   resonance allows for phase transitions in the speed and bandwidth of
4   information exchange to occur at various organizational levels,
5   allowing previously disordered systems to self-organize and thus
6   become coherent. The speed and bandwidth of information flows
7   achieve a step change through such a phase transition, allowing for the
8   unity of consciousness in each moment.
9   The primary insight offered in the present paper is that conscious-
10   ness is a product of resonance chains[1] of various information/energy[2]
11   pathways, and that the spatial and temporal boundaries of any particu-
12   lar conscious entity is established by the slowest-frequency shared
13   resonance within that conscious entity, for each particular informa-
14   tion/energy pathway. Shared resonance and resulting resonance chains
15   are the key mechanisms for self-organization and are constantly
16   changing in most entities (Walleczek, 2000). Thus, the spatial and
17   temporal boundaries of conscious entities will be constantly changing
18   at least a little. Most combinations of consciousness, in which less
19   complex entities combine into more complex entities in biological
20   structures like mammal brains, will be comprised of a nested
21   hierarchy of conscious entities, with one dominant conscious entity in
22   each moment, without extinction of the nested entities' consciousness.
23   This lack of extinction of subsidiary entities distinguishes the present
24   approach from integrated information theory and other theories that
25   assume the extinction of nested conscious entities, resulting in only
26   one macro-conscious entity left (this is, for example, IIT's 'exclusion
27   principle').

---

[1]   Bandyopadhyay (2019) has developed a sophisticated approach to resonance chains in a
broad theory of consciousness he calls the fractal information theory (FIT) of con-
sciousness. Resonance in GRT is similar to its role in FIT, but GRT adopts a meta-
physically foundational role for resonance through its general congruence with
Whitehead's process philosophy and the 'actual entities' that are the 'final real things'
that comprise the world (Whitehead, Griffin and Sherburne, 1929; Hunt and Schooler,
2019; Hunt, 2019a).

[2]   Information is generally defined as a subjective aspect of the physical world, whereas
energy is an objective aspect; but *in the context of GRT* I am using these terms inter-
changeably because I define information as 'aspects of energy that we can measure'. All
physical dynamics consist of nothing more than energy flows, but those energy flows
that we can measure may be labelled 'information' and quantified under established
information theoretic concepts. I will, however, refer to 'information/energy flows'
simply as 'information flows' from now on in this paper, for simplicity's sake.

1   The rest of this paper provides a heuristic for calculating the spatial
2 and temporal boundaries of candidate conscious entities, as well as the
3 capacity for phenomenal consciousness as a function of the spatial and
4 temporal boundaries of each entity.

2. Calculating Spatial Boundaries and Phenomenal Capacity in General Resonance Theory

Step 1: Inductively identify candidates for the combination of consciousness

9 The first step in calculating the spatial boundaries of a candidate
10 complex conscious entity is to consider, inductively, what constituents
11 are likely to be resonating synchronously and, as such, to be candi-
12 dates for a structure that combines micro-conscious entities into a
13 particular macro-conscious entity. We label such a candidate for com-
14 bined consciousness a 'putative combined consciousness' or PCC.
15 Inductive judgments about what may constitute a PCC will necessarily
16 be based on the human experience of consciousness and what
17 structures we can, accordingly, expect to enjoy some degree of con-
18 sciousness, based on observed behaviour similar to what we see in
19 humans and other creatures that most humans would agree are con-
20 scious. We can label these types of behaviours the 'behavioural
21 correlates of consciousness' (Tononi and Koch, 2015; Hunt and
22 Schooler, 2019; Hunt, Ericson and Schooler, ms).

23   *Definition 1.* CC ≡ a combined consciousness, any group of two
24   or more conscious entities that combine to produce a higher-level
25   consciousness.
26   *Definition 2.* CC_L ≡ the largest combined consciousness in the
27   relevant context.
28   *Definition 3.* PCC ≡ a putative combined consciousness, based
29   on inductive judgments about the human experience of
30   consciousness.

31 Some examples for applying this inductive methodology for identi-
32 fying a PCC include (without pre-judging whether any of these combi-
33 nations should be considered, in fact, conscious):

34   ● measuring EEG or MEG in the various neurons and groups of
35   neurons that comprise human and other mammalian brains;
36   ● measuring EEG or MEG in human coma patient brains;

- measuring chemosensory or electrochemical pathways in non-mammalian neurons like *Drosophila* or *C. elegans* (Gelperin, 2014), and other means for studying comparative cognition between species;
- measuring EEG or MEG in the non-neuronal biological systems that comprise invertebrate sensory systems (jellyfish that have eyes, for example);
- biochemical communication systems in slime moulds (Vallverdú *et al.*, 2018);
- calculating information flows and speeds in computer systems that pass a Turing test, when and if such feats become possible;
- or simply measuring information flows based on resonance chains in any artificial computer.

In each example, we may consider, as the first step in our suggested heuristic, whether the collection of entities examined may, inductively, be likely to enjoy some variety of combined consciousness. Inductive judgments about what should be considered a PCC will change over time as more data become available with respect to the presence of consciousness in various entities in nature and even possibly in human creations such as artificial intelligence.

Step 2: Calculate the primary resonance frequencies and
synchrony in the putative combined consciousness

The second step is to determine the primary resonance frequencies of whatever information/energy exchange processes (chemical, electro-chemical, electrical, etc.) are present in the PCC. For example, in human brains it appears that electrical and electrochemical informa-tion pathways (what we can also label 'resonance chains' as a unifying feature of such dynamics) are the most significant, though other pathways may also be significant (Koch, 2004; Hunt and Schooler, 2019; Hameroff and Penrose, 2014).

Once the primary resonance frequencies are determined we can calculate the degree of synchrony/coherence between the putative constituents of the PCC. The degree of synchrony is important because it determines how much information can flow between different constituents of the PCC.

The highest *bandwidth* shared resonance chain will generally be most relevant for determining the contents of consciousness, but the slowest shared resonance *frequency* of the highest bandwidth reso-nance chain ('slowest shared resonance' or SSR) will define the

1   boundaries of the *largest combined consciousness*, CC_L, at least with
2   respect to that particular resonance chain. This is the case for two
3   reasons:

4   (1) Faster shared resonance frequencies will lead to nested CCs that
5   have their own more localized awareness. In this manner, the
6   slowest shared resonance frequency will be the 'slowest common
7   denominator' and thus the limiting factor of the CC_L.
8   (2) Each resonance cycle is a snapshot that incorporates available
9   information within each cycle, and each resonating structure at
10   least partially resets after each cycle. Fries (2015) states: 'In the
11   absence of coherence [resonance], inputs arrive at random phases
12   of the excitability cycle and will have a lower effective
13   connectivity.' Conversely, inputs that arrive synced to the same
14   excitability cycle will propagate faster and with greater band-
15   width. Slower frequencies will generally travel faster (Dehaene,
16   2014, p. 137). In the present framework, these principles apply to
17   all resonating structures (i.e. all physical structures), not just
18   neurons.

19   Accordingly, *the speed at which new information can be incorporated*
20   *into the PCC, within each cycle, is the limiting factor for the spatial*
21   *extent (boundary) of the PCC*. Restating this as a principle:

22   *Principle 1*. The slowest shared resonance frequency (SSR)
23   defines the spatial boundaries of the largest combined conscious-
24   ness (CC_L) for each resonance chain.

25   The CC_L may also be described as the *dominant consciousness*,
26   because its intentions and desires will supersede (without
27   extinguishing) those of any subsidiary (nested) consciousness(es) that
28   is present, if such intentions and desires are in conflict between levels.
29   The boundaries of the CC_L will generally change in each resonance
30   cycle, sometimes subtly and sometimes substantially, as we can
31   observe in introspecting about the features of our individual human
32   consciousness — a very immediate example of a CC_L.
33   Parts of the CC_L will display higher frequency resonances than the
34   SSR, but those higher frequencies won't be shared by all regions of
35   the CC_L and thus won't define the boundaries of the CC_L. Rather, they
36   would define the boundary of a *subset* of the CC_L that would then
37   have its own level of localized consciousness. As such, in most
38   biological-scale structures, each CC_L is a nested hierarchy of various
39   different resonating frequencies and smaller CCs (or CC_n, for 'nested'

combined consciousness; each CC_L will be combined usually of many CC_n). Each level of resonance will have its own level of consciousness, feeding up to the next level of consciousness to the degree that the lower level achieves a shared resonance with the higher level. This relationship constitutes a nested hierarchy of conscious entities all interrelating in a web of radial causality (bottom-up and bottom-down).

For example, Klimesch (2018) fleshes out a 'frequency architecture' in animals and proposes a 'binary hierarchy brain body oscillation theory' of consciousness. Klimesch's theory highlights the presence of many levels (he counts at least 12 levels) of 1:2 frequency relationships (the higher frequency is twice that of the lower frequency; hence 'binary'), from fast gamma electrical field synchrony at the high end to BOLD (blood oxygen level depending signal) as measured by fMRI.

Another example, at the smallest of biological scales: recent research has probed high terahertz-level oscillations in tubulin molecules that comprise the ubiquitous microtubule scaffolding of most cells (Craddock *et al.*, 2017). These frequencies are far faster (that is, a higher number of cycles per second) than those observed in global or local EEG or MEG data. Cycle times and wave propagation velocities will, as discussed, limit the boundary of the PCC in each moment, giving rise to the second principle:

> *Principle 2*. For each CC_L the shared resonance frequency will diminish as distance increases between the constituent resonating structures.

This means that as distance between constituents increases, the shared resonance frequency diminishes, and vice versa. Both of these principles may be tested empirically. Early empirical support for Principle 2 may be found in examining retina–brain, heart–brain, and stomach–brain shared resonances, with an SSR of 3–4 Hz, 1.48 Hz, and 0.05 Hz, respectively, for each type of coupling.

It is important to highlight the fact that higher frequency resonances, such as those examined by Craddock *et al.* (2017) at the terahertz sub-neuronal level, may be present in many locations within a larger-scale CC_L, allowing for those nested combined-consciousness entities (CC_n) to be subsumed into the larger CC_L. If they do not achieve a shared resonance with the higher spatial levels (slower frequencies) they can remain as a CC at their own scale and operate independently of the CC_L. In such a case these would be *parallel*, rather than nested,

1   conscious entities, operating at different spatial and temporal scales in
2   proximity to each other.
3   Figure 1 illustrates these terms and principles using abstract resona-
4   ting structures combining into various CC_n and ultimately into a single
5   CC_L, in a nested hierarchical process of increasing complexity and
6   thus an increasing capacity for phenomenal consciousness with each
7   additional level of integration through shared resonance.

8
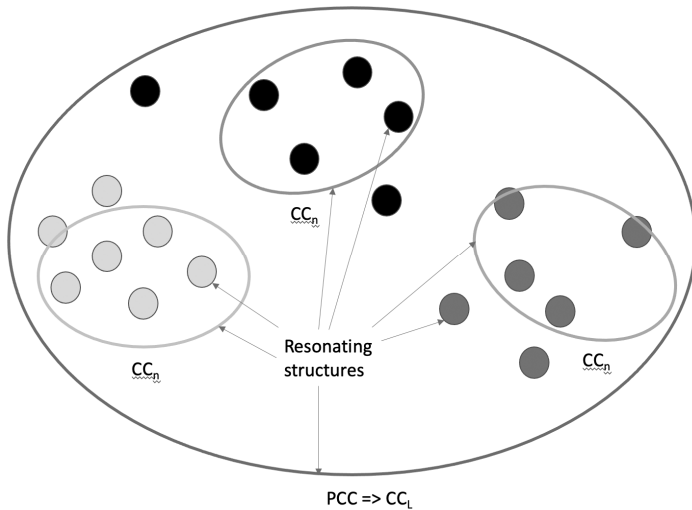
9   *Figure 1*. A PCC becomes a CC_L through combination of many smaller
10   resonating structures. The abstract small circular entities outside of the
11   ovals do not achieve a shared resonance and thus do not combine. They
12   maintain their own level of consciousness without being subsumed into a
13   larger conscious entity. Abstract small circular entities inside the ovals
14   become part of the CC_L but still maintain their own level of consciousness.
15   As Whitehead, Griffin and Sherburne (1929) state: 'the many become one
16   and are increased by one.' There is no extinction through exclusion, as
17   there is in integrated information theory.

18   Once the various resonance chains have been adequately identified for
19   further examination, the degree of resonance may be calculated. There
20   is a vibrant field of study that focuses on the degree of synchrony (a
21   species of resonance) in oscillating phenomena. Since an axiom of
22   GRT is that all things resonate at some frequency (Hunt and Schooler,
23   2019), and thus all things are oscillating phenomena, synchrony
24   indexes of various kinds may be adapted for whatever physical
25   oscillating structures are the object of study.

With respect to animal brains, there is already a long tradition of using various synchrony indexes to establish the degree of synchrony within different electromagnetic field oscillations. In the mammal brain, electrical field frequency bands and their 'centre frequencies' have been labelled as follows: (1) delta 2–4 Hz; (2) theta 4–7 or 8 Hz; (3) alpha 8–12 Hz; (4) beta 16–25 Hz; (5) gamma 30–50 Hz (Klimesch, 2018). These frequencies have certain functions and their overlapping and nested synchronizations, and even harmonizations (*ibid.*; Siebenhühner *et al.*, 2020; Rodriquez-Larios and Alaerts, 2019), constitute a complex system of interlocking functions that couple and decouple frequently depending on circumstances and needs.

Establishing the degree of synchrony between constituents of the PCC will allow calculating the information bandwidth for each resonance chain, which is, as discussed below, integral to calculating not only the spatial and temporal boundaries of consciousness but also the contents of consciousness. The higher the synchrony value for a particular resonance chain — or system of coupled oscillators, in other words — the higher the information bandwidth, all else equal.

In practice, in any complex system of coupled oscillators, calculating the various synchrony indexes will be challenging — but still far easier than calculating information flows for complex systems that are not comprised of coupled oscillators. Quantifying information flows is important for calculating the perception index and connectivity index, discussed below, which together lead to calculating the capacity for phenomenal consciousness in any particular PCC.

Lachaux *et al.* (1999) established a commonly-used synchrony index, the phase-locking value (PLV). Ghanbari and Moradi (2020), a recent review of different kinds of phase-locking value methods, proposed a new synchrony index, the 'fuzzy scale invariant feature transform phase-locking value' or FSIFT-PLV. This index uses a phase estimation approach based on reduced interference Rihaczek distribution. Phases of signals are calculated as a time-frequency map. For each pair of signals, scale-invariant feature transform (SIFT) descriptors are extracted from these maps. Then, the proposed fuzzy framework is used for quantifying similarity between maps, which is a synchrony measure.

The authors also compare their new measure to a number of existing similar measures, two of which comparisons are useful here. Figure 2 includes two of the tables presented, comparing the various indexes based on accuracy under certain conditions, and also the amount of

1   computer time required to calculate the index values. As is evident,
2   there are trade-offs between these two features. Based on these trade-
3   offs, in most cases the ciPLV (corrected imaginary phase-locking
4   value) index may be the most useful measure because it is both
5   relatively accurate and requires relatively little computing power.

Table 3
Error associated with calculating phase synchrony.

Method	PLV	PLI	WPLI	dwPLI	ImC	ciPLV	FSIFT-PLV
Error (RMSE)	0.194	0.319	0.225	0.198	0.473	0.206	0.058

6

Table 8
Comparison the execution times (sec).

Method	FSIFT-PLV	WPLI	PLI	ImC	ciPLV
Execution time	9470.93	374.65	243.89	411.63	2.60

7

8   *Figure 2*. Ghanbari and Moradi's (2020) comparisons of various synchrony
9   measures.

10   I offer this discussion of synchrony indexes as a quick overview of the
11   topic. What index(es) should be used in each circumstance in relation
12   to GRT will vary.

13   *Step 3: Calculate the spatial boundaries of the PCC*

14   The third step is to employ these principles to calculate the spatial
15   boundary of the PCC by calculating the distance, from the approxi-
16   mate edge[3] of the PCC, that resonance chains, and their associated

---

[3]   It is the edge rather than the centre of the PCC that is relevant for calculating the spatial
boundaries because, at any scale that is currently measurable, a moving pattern of reso-
nance forms the sequential basis for calculating the boundary of the PCC in the next
moment. Moreover, the phase transition in the speed of information flows that is
important for the formation of macro-consciousness will in most cases render any
information that reaches the edge of the moving resonating structure 'within' that
structure for the purposes of being included in the relevant macro-conscious experience.
In other words, once the edge of the resonating structure is reached, from outside the
PCC, information flows within that structure act akin to a superconductor, by achieving
a phase transition in the speed of information flows, and may be integrated with other
information 'within' the PCC in effectively the same instant. Empirically, there will
always be some elapsed time for each level of information processing to be passed up
the chain within each PCC, and eventually integrated into the dominant consciousness,

1   information flows, can travel within the relevant frequency cycle time.
2   This step will be an iterative process because conclusions about the
3   approximate edge of the PCC will change with each measurement.
4   Accordingly, this heuristic will follow a generally Bayesian logic of
5   increasingly accurate iterations without any final 'correct' answer.
6   Components of the PCC that are within the spatial boundary formed
7   by this speed limit are included in the CC, in each iteration at time t,
8   and those that are outside this boundary are not perceived and thus are
9   not included in that moment of consciousness. Eq. 1 describes this
10   simple formalism.

11   Eq. 1 $x_e = v/f$
12   which becomes: $x_e = (m/s)/(cycle/s)$
13   which becomes: $x_e = m/cycle$

14   Accordingly, the distance, x_e, from the edge of the resonating structure
15   in the present cycle to the furthest edge of the same resonating
16   structure in the next cycle, in each direction, is equal to the velocity
17   (v) of the specific resonance chain (i.e. energy/information pathway,
18   or causal interaction) divided by the frequency (f, Hz, or cycles per
19   second).
20   Figure 3 illustrates this step in the human neocortex, which is
21   postulated to be connected over its extent by long-range synchrony
22   (e.g. gamma synchrony is a commonly observed long-range
23   synchrony in the mammal cortex, but gamma synchrony is not the sole
24   type of long-range synchrony and gamma synchrony may be observed
25   even without macro-consciousness; Hunt, 2020).
26   For example, if we are looking at 40 Hz electric field gamma
27   synchrony in the mammal brain (40 cycles/s), and a wave propagation
28   velocity of approximately 1.4 m/s (the velocity of the electric field
29   itself is far faster, as we'll see below), we obtain $x_e = 1.4/40 = 0.035$
30   metres per cycle for the maximum distance from the edge of the PCC
31   in that direction (as Bahramisharif *et al.*, 2013, state, velocity figures
32   for various kinds of wave propagation in the cortex are generally still
33   quite provisional since the science in this area is still new). Accord-
34   ingly, each 1/40th of a second of gamma synchrony may result in a
35   changing PCC of up to 0.035 m/s. This scale and pace of change

---

but all information that does reach the highest level is effectively integrated in a single
moment into a unified conscious experience. This is what it means for consciousness to
be unified.

1   seems to fit with observed gamma synchrony field dynamics in the
2   mammal cortex.

3
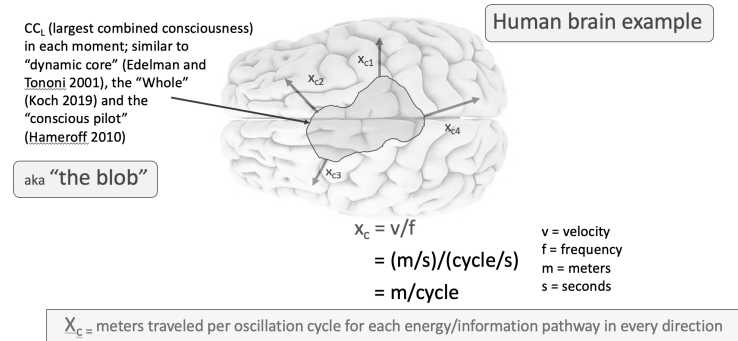
4   *Figure 3*. Calculating spatial boundaries of a PCC or CC_L using long-range
5   synchrony in the human neocortex as an example. X_e is the distance from
6   the current edge of the PCC/CC_L to the edge in the next cycle in each
7   direction. These values will be changing in each cycle due to the cortical
8   dynamics of electromagnetic fields and other biophysical information path-
9   ways. 'The blob' is whatever shape the 'dynamic core' (using Edelman and
10   Tononi's, 2001, terminology) takes in each moment.

11   Table 1 presents various energy pathway (resonance chain) velocities,
12   frequencies, and distances travelled in each cycle, organized from
13   fastest to slowest velocity.
14   Weak electric fields, or what is described as *ephaptic coupling*, are a
15   relatively newly discovered form of brain communication that have in
16   recent years become accepted by many as a real effect that supervenes
17   on but is not the same as electrochemical energy flows. That is,
18   neuronal communication can occur through pathways that don't
19   require axonal or dendritic connections (Chiang *et al.*, 2019; Qiu *et
20   al.*, 2015). Hunt and Schooler (2019) discuss the possibility that
21   human consciousness may primarily be a product of electric fields,
22   possibly mediated also by other fields.
23
24
25
26
27
28
29
30

Energy pathway	Velocity (v)	Frequency (f)	Distance travelled per cycle (v/f)
Terahertz-level tubulin resonance (Craddock *et al.*, 2017)	Possibly > c	613 THz	0.0049 m*
Electrochemical pulses through axons (Siegel, Sapru and Siegel, 2019)	80–120 m/s	Various	Various
Theta waves propagation in the human whole brain (Zhang and Jacobs, 2015)	1–5 m/s	~5 Hz	~0.6 m
Gamma waves propagation in the human whole brain (Bahramisharif *et al.*, 2013)	0.7–2.1 m/s	~40 Hz	0.035 m
Beta waves propagation in the human whole brain (Takahashi *et al.*, 2011)	0.23 m/s	~25 Hz	0.0092 m
Weak electric fields propagation ('ephaptic coupling') (Chiang *et al.*, 2019; Qiu *et al.*, 2015)	0.1 m/s	<1 Hz	~0.1 m
Gap junction sharp wave 'ripples' in the mouse brain (Maier, Nimmrich and Draguhn, 2003)	0.016 m/s	200 Hz	0.00008 m

1 * If we assume 10,000 c, as Salart *et al.* (2008) suggest is the minimum speed
2 of collapse.

3 *Table 1.* Various energy pathway and field propagation velocities and
4 frequencies in mammal brains, ordered by descending velocity.

5 Qiu *et al.* (2015) also observe: '0.1 m/s is a common propagation
6 speed [for neural propagation of various types] regardless of experi-
7 mental models, therefore a shared fundamental mechanism may
8 underlie these neural propagations.' This is an intriguing clue that
9 researchers don't seem to have plumbed sufficiently at this juncture,
10 though Zhang and Jacobs (2015) find theta propagation velocities in
11 the human hippocampus to be 1–5 m/s, diverging markedly from the
12 earlier data that Qiu *et al.* (2015) relied upon.
13   While propagation speeds may be relatively slow for most of the
14 energy pathways described in Table 1, it is also the case that once a
15 field has extended its reach over a certain area, if that field is electro-
16 magnetic in nature, transmission of information within that field will
17 occur at velocities up to the speed of light (John, 2001; Jones, 2013,
18 stating 'John's experiments (2001, pp. 185ff.) show that different

1   brain areas synchronize their firing with *zero time lag*', emphasis in
2   original, though it is important to note that there is not a literal zero
3   time lag, just a very short lag). It is these data that motivated Eq. 1 and
4   its assumption that processing time is close to zero (though not
5   actually zero) for any information 'within' the PCC.
6   Once we calculate the maximum distance from the present edge of
7   the dominant resonance frequency, and thus establish the new bound-
8   ary of the PCC in each direction, we can drop the 'P' in PCC and
9   describe the newly bounded structure as a CC. There will generally be
10   far more than one CC present, however, in any PCC, as discussed
11   above, due to the nested hierachy that constitutes most CCs.

12   *Step 4: Calculate the perception index*

13   The fourth step is to calculate the 'perception index' (PI or π) of the
14   putative CC. PI refers to the perceptual bandwidth of the CC and is, in
15   biological entities, based on the various biological sensory pathways
16   such as vision, touch, etc.[4] This value represents, essentially, the
17   connections from the CC_L to the <u>external</u> world or, in the case of
18   dreaming, data created internally and presented to the PCC as though
19   they were external data. Eq. 2 provides a method for calculating the
20   sensory bandwidth (PI) of any CC.

21   Eq. 2 $\pi(CC) = \sum I\left(CC, O_j^{\infty}\right)$

22   In Eq. 2, the sensory bandwidth of a CC, in each iteration, is the sum
23   of all perceptual data received by the CC from the various objects of
24   perception, O_j. An 'object' is literally any datum presented to per-
25   ception.[5] This measurement will in any interesting case not be simple
26   due to the number of causal connections between the CC and the rest
27   of the world, and the difficulty in measuring these causal connections.

---

[4]   Perceptual bandwidth doesn't necessarily mean perception external to the brain, in the
      case of human complex subjects and probably for other mammalian consciousness
      either. For example, during dreaming there is clearly a high capacity for phenomenal
      content, with the 'external' information supplied by certain parts of the brain instead of
      external perception. In the framework offered here, the parts of the brain that supply
      dream data to the CC_L may be considered as 'perception' and are thus quantified as part
      of the PI.

[5]   All *objects* of perception are themselves, in the Whiteheadian process philosophy ontol-
      ogy that GRT is roughly modelled on, *subjects* in a later moment, as they cycle from
      physical to mental poles in their own cycle times (Hunt, 2019; Whitehead, Griffin and
      Sherburne, 1929).

1 Casarotto *et al.* (2016) provide one means for simplifying this kind of
2 measurement by using a perturbational complexity index (PCI) that
3 approximates the causal connections that Tononi's IIT relies on. PCI
4 and related measures may also be useful in the context of GRT.
5 We can, as a working example in applying this framework, consider
6 fruit fly perception. Much is known about fruit flies, so they are a
7 good candidate for fleshing out this framework. To simplify further
8 for present purposes, let's consider the fruit fly visual system as an
9 ostensibly separate neural system (it is, of course, not actually separate
10 from the rest of the fly's neural system).
11 Fruit flies have compound eyes with about 760 *ommatidia* (simple
12 eyes), each of which have eight photoreceptor cells (Hardie and
13 Raghu, 2001). If we assume 12-bit colour resolution for each photo-
14 receptor, the visual bandwidth of the fruit fly amounts to about 72,960
15 (12 x 760 x 8) bits in each moment, the result of applying Eq. 2 for the
16 visual system of a fruit fly.[6] As an index, this value for PI needs to be
17 normalized, however, to avoid unnecessarily large numbers in com-
18 paring sensory bandwidth. Using Table 2 we translate this 72,960 bit
19 rate to a normalized value of 4 on a normalized scale for PI that spans
20 from 0 to 12.
21

Perception index (PI/π) raw value	Normalized PI/π value
0–100 bits per cycle	1
101–1,000 bits per cycle	2
1,001–10,000 bits per cycle	3
10,001–100,000 bits per cycle	4
100,001–1,000,000 bits per cycle	5
1,000,001–10,000,000 bits per cycle	6
10,000,001–100,000,000 bits per cycle	7
100,000,001–1,000,000,000 bits per cycle	8
1,000,000,001–10,000,000,000 bits per cycle	9
10,000,000,001–100,000,000,000 bits per cycle	10
100,000,000,001–1,000,000,000,000 bits per cycle	11
1,000,000,000,001–10,000,000,000,000 bits per cycle	12

22 *Table 2*. Perception index normalized values.

---

6 Fruit flies have low spatial visual resolution compared to humans, but very good visual
temporal resolution, at about 200 'frames per second'. By contrast, humans cannot
experience much more than about 18 'frames per second' of visual input, though there
are some exceptions.

1   *Step 5: Calculate the connectivity index*

2   The fifth step is to calculate the 'connectivity index' (CI or ψ) of the
3   CC. CI refers to information processing power or <u>internal</u> connect-
4   ivity, which is a measure of the intra-connectedness of the CC. More
5   specifically, it measures the types of resonance chains internal to the
6   CC_L that connect the various CC_S that, in combination, comprise the
7   larger and unified resonating structure. This concept is derived from
8   and is similar to Edelman and Tononi's (2001) 'neural complexity'
9   measure (see fn. 7 below).
10   Connectivity in this context refers to the presence and quantity of
11   internal energy/information pathways — differences that make a
12   difference to the resonating structure. Connectivity implies the trans-
13   mission of something internal to the CC and this 'something' is at its
14   root simply causal influence, something that results in a difference to
15   the system. CI quantifies the internal connectivity of the CC, the
16   degree to which information flows between different parts of the CC.
17   CI scores also fall on a normalized scale between zero and 12 (Table
18   3).
19   Eq. 3 formalizes CI (ψ) for any given CC.[7] X_j^k is a subset of the
20   CC's possible constituents, and MI (mutual information) is a two-way
21   information/causal flow between each part and the rest of the CC:

22   Eq. 3. $\psi(CC) = \sum\ <MI(X_j^k; CC - X_j^k)>$

23   ψ for any CC will, thus, be the sum of the mutual information between
24   each subset of the CC and the rest of the CC. PI and CI will entail
25   complicated calculations in any biological structure because of the
26   physical complexity involved in any biological structure. I discuss this
27   limitation further below.

---

[7]   Edelman and Tononi (2001, p. 130) offer a similar measure, described as 'neural com-
plexity', but neither this measure nor their theory more generally has a direct bearing on
phenomenal content. This is the case because, despite their assertions that their theory
explains qualia as well as the workings of the brain, their theory is expressly materialist
in nature and offers no link between functional explanations of the brain and phenom-
enal content. They do not offer any psychophysical laws or bridging principles between
the physical and phenomenal realms. Their measure of neural complexity is character-
ized, building on the definition of mutual information described in their book and pub-
lished papers, as, where MI is mutual information, X_j^k is a specific subset of the whole,
and X is the whole:

$$C_N(X) = \sum_{k=1}^{n/2} <MI(X_j^k; X - X_j^k)>$$

1   Looking again to the fruit fly as an example for applying the frame-
2   work, the fruit fly's brain is mostly devoted to visual processing and
3   contains about 100,000 neurons (Rein *et al.*, 2002). If we assume an
4   average 100 dendrites for each neuron, we have about 10,000,000
5   synapses, which are the internal connections quantified by CI in this
6   case. We would also determine what neural subunits exist in the fly
7   brain and quantify interconnections between neural subunits in
8   addition to the simple internal connectivity of all synaptic connections
9   to each other. These data are steadily being discovered in work on the
10 various 'connectomes' in different organisms. We would also consider
11 other relevant information flows at the subneuronal level, as explored
12 by Craddock *et al.* (2017), Hameroff and Penrose (2014), and other
13 publications. The complexity in quantifying these levels of
14 connectivity is daunting. Building upon the considerable research
15 efforts to identify the connectome in the human and other brains, we
16 can now begin to flesh out a 'resonome' structure that is comprised of
17 the commonly observed resonance frequencies associated with various
18 functions.
19   Despite this complexity, for the purposes of this fruit fly visual
20 system example, we can translate this calculation to an estimated
21 normalized CI value of 4 (Table 3). Again, the specific value doesn't
22 particularly matter at this time since it's only an example to show how
23 the framework works. The quantified interconnectedness of complex
24 CCs will in most cases be significantly higher than the quantified PI
25 for the same CC, so in general the CI will be higher than PI in
26 biological systems.
27

Connectivity index (CI or ψ) raw value	Normalized CI/ ψ value
0–100 bits per cycle	1
101–1,000 bits per cycle	2
1,001–10,000 bits per cycle	3
10,001–100,000 bits per cycle	4
100,001–1,000,000 bits per cycle	5
1,000,001–10,000,000 bits per cycle	6
10,000,001–100,000,000 bits per cycle	7
100,000,001–1,000,000,000 bits per cycle	8
1,000,000,001–10,000,000,000 bits per cycle	9
10,000,000,001–100,000,000,000 bits per cycle	10
100,000,000,001–1,000,000,000,000 bits per cycle	11
1,000,000,000,001–10,000,000,000,000 bits per cycle	12

28   *Table 3*. Connectivity index normalized values.

1 *Step 6: Calculate the omega value based on PI and CI*

2 The next step in the heuristic is to calculate the CC's capacity for
3 phenomenal content, or what we can label simply as 'the capacity for
4 consciousness'. To obtain this figure we multiply PI and an adjusted
5 CI to obtain the omega value, Ω, which is the end result of this
6 heuristic framework for quantifying the capacity for phenomenal con-
7 sciousness in each cycle (Eq. 4). Omega is calculated as an adjusted
8 product of PI and CI because C_M, the coupling metric, represents the
9 degree to which perception data (PI) is shared unequally by the CC's
10 subsets. C_M, following Edelman and Tononi (2001) and their 'com-
11 plexity matching' constant, quantifies the degree to which perception
12 information is shared by each part of the system (X_j^k). 'Shared' means
13 that the perception data achieve a difference that makes a difference to
14 that subset.

15 Eq. 4. $\quad \pi * C_M * \psi = \Omega$

16 Accordingly, the CC's capacity for phenomenal consciousness is the
17 adjusted product of its perceptual bandwidth and its internal
18 connectivity. This equation is a potentially powerful tool for gaining
19 real knowledge of subjective experience because knowledge of three
20 of the variables allows us to calculate the value of the fourth variable.
21 The rationale for this equation is simple: each percept is, upon being
22 incorporated into the CC, incorporated, at least to some degree, into
23 all of its processing nodes, which is what we mean by 'integration' in
24 this context. Keep in mind that the processing nodes that are part of
25 the CC in each iteration are determined by the spatial extent Eq. 1: x_e
26 = m/cycle.
27 As a simple example, we can focus on an artificial neural network
28 consisting of 100 'neurons'. We can postulate a CI value of 2, in order
29 to demonstrate how this equation works. A CI of 2 indicates that each
30 node is rather slow at sending its possible data to all other connected
31 nodes. And we assume that electrical currents are the connections
32 responsible for such information flows between these artificial
33 neurons. We can also postulate a PI value of 1, based on the paucity of
34 data we feed this information-starved mini-network. With CI = 2 and
35 PI = 1, and a postulated coupling metric of 1, we calculate an omega
36 value of 2 (1 x 1 x 2 = 2), far down the scale from 0 to 144. Under the
37 criteria described thus far, this simple network would have a
38 commensurately simple phenomenal capacity.

1   Recalling our estimated PI value of 4 and CI value of 4 for the fruit
2   fly's visual system, and again a postulated but not realistic coupling
3   metric of 1, we obtain an omega of 16, on a scale of 0 to 144, for the
4   same fruit fly's visual system. In actuality there is no separation of
5   senses in the complex entity that is a fruit fly. But, again, this is a
6   simplified example to illustrate the formalisms offered here.
7   Table 4 provides more examples of possible omega values. It is
8   important to stress that these are speculative examples of how the
9   framework may be applied in the future. All values provided are rough
10   estimates and based on a normalized scale from 0 to 144, based on the
11   normalization scales provided in Tables 2 and 3 (both of which extend
12   to 12). The examples also assume $C_M = 1$, which will generally not be
13   the case because of imperfect sharing of sensory data throughout the
14   informational core of the CC_L.
15

Example	Omega/Ω Value
Electron	0.1
Atom	1
Macromolecule	3
Virus	5
Paramecium	8
Fruit fly visual system	16
Fruit fly	25
Rat	50
Bat	55
Cat	60
Chimp	70
Human	85
Artificial superintelligence[8]	100
?	144

16   *Table 4*. Possible examples of various omega values (for a single cycle).

17   *Step 7: Calculate the frame rate (temporal resolution) of the CC*

18   A final but important consideration relates to the fact that omega pro-
19   vides a measure of the capacity for phenomenal content for a single
20   cycle, a single iteration of the slowest shared resonance of the CC_L.
21   Calculating omega for each iteration cycle of the entity at issue pro-

---

8   Based on resonance principles/neuromorphic architecture rather than feedforward/von
     Neumann architecture (see Koch, 2019).

1   vides a comparison across entities for each 'frame' of consciousness,
2   which is a useful comparison. However, conscious entities may have a
3   vastly different temporal frame rate, giving rise to far higher phenom-
4   enal capacity for a given timespan for entities that have higher frame
5   rates.
6   For example, we can speculate about artificial superintelligence
7   (ASI), which has been loosely defined as AI that is at least 1,000
8   times more intelligent than humans. One way that this could be
9   achieved is to simply have a far faster rate of cognition than humans
10   enjoy, and a faster processing rate is a natural advantage for silicon-
11   based intelligence when compared to biological intelligence like
12   humans. If we assume for present purposes that an ASI built on
13   resonance principles did indeed enjoy the capacity for phenomenal
14   consciousness commensurate to its processing and sensory power, per
15   the quantification heuristic described here, then we would expect an
16   ASI that processed information 1,000 times faster than the average
17   human to also have approximately 1,000 times the average human's
18   capacity for phenomenal content.
19   A final equation expresses this important detail, with Δ_t symbolizing
20   any specific duration (such as 1 sec, 1 minute, etc.) and f_{SSR} the
21   frequency of the slowest shared resonance:

22   Eq. 5: $\Omega(\Delta_t) = \Omega * f_{SSR} * \Delta_t$

23   Using our ASI example, and a postulated f_{SSR} of 1,000 Hz (1,000
24   cycles per second), this would result in the following (unnormalized)
25   omega per second: Omega(1 sec) = 95 x 1,000 Hz x 1 second =
26   95,000.
27   A normal human, as another example, if we postulate an f_{SSR} of
28   40 Hz, we arrive at an (unnormalized) omega per second of 85 x 40
29   Hz x 1 second = 3,400. This is a far smaller value than the 95,000 we
30   calculated for our built-on-resonance-principles ASI example.
31   Figure 4 summarizes the six-step heuristic I've described herein,
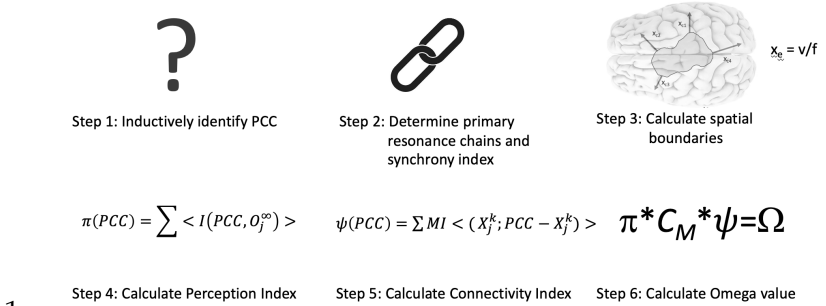32   omitting step seven for the sake of simplicity.

Step 1: Inductively identify PCC | Step 2: Determine primary resonance chains and synchrony index | Step 3: Calculate spatial boundaries

$$\pi(PCC) = \sum <I(PCC, O_j^\infty)> \qquad \psi(PCC) = \sum MI <(X_j^k; PCC - X_j^k)> \qquad \pi * C_M * \psi = \Omega$$

Step 4: Calculate Perception Index | Step 5: Calculate Connectivity Index | Step 6: Calculate Omega value

Figure 4. Summary for calculating spatial boundaries and capacity for phenomenal content.

3. Limitations of the Approach

This mathematical heuristic for GRT calculates the spatial boundary of any conscious entity in each moment and a simple scalar value for phenomenal capacity of that entity. This framework may provide a useful set of tools to probe the capacity for consciousness at all scales. The main value of this approach will be to provide for comparisons across all levels of consciousness and physical complexity.

There are some limitations in employing this relatively simple approach, however, and I'll discuss the more obvious ones here.

3.1. A scalar value can give no indication of the different types of conscious experience available to comparably complex conscious entities, or of the different types of consciousness present in the same conscious entity in each moment

Omega is a measure of the *capacity* for different types of phenomenal consciousness, not a measure or characterization of any *actual* phenomenal consciousness. It is, rather, a means for measuring comparative cognition and comparative consciousness.

IIT does suggest methods for characterizing consciousness, in addition to a quantification framework (Oizumi, Albantakis and Tononi, 2014). IIT's tools for characterizing phenomenal experience — depiction of visual 'constellations' for each possible quale in a given 'complex' — rather than only quantifying the capacity for such experiences, may be compatible with GRT, and may be a useful addition to the tools offered here. That is, IIT's constellation-qualia characterization tools may be compatible with GRT. This is an area

1 for future work with respect to GRT's development as an alternative
2 or complement to IIT.

3.2. Calculating PI and CI in any biologically-complex entity is
difficult

5 As discussed above, any biologically interesting system examined in
6 the GRT framework will be difficult to quantify accurately because of
7 the complexity of the biological structures involved. Even relatively
8 simple biological systems like *Drosophila* or *C. elegans* have great
9 depth that will require, at least early in the development of measures
10 of comparative consciousness, many simplifying assumptions. How-
11 ever, this is the case for any theory that attempts to make sense of the
12 biological world, and it will require, like any such theory, dedicated
13 effort by many researchers to develop reliable simplifying tools for
14 making meaning quantifications. Over time, such techniques will
15 improve and more accurate quantifications will become possible. One
16 such example has already been developed with respect to integrated
17 information. Casarotto *et al.* (2016; with Tononi as a co-author),
18 mentioned above, employ a simplifying approach, the perturbational
19 complexity index, as a very rough proxy for integrated information.
20   Significant simplification in calculating PI and CI, however, is
21 possible with a focus on the information pathways of electromagnetic
22 oscillating fields using EEG, MEG, and related tools, as discussed
23 above in relation to the various synchrony indexes. A recent preprint
24 study, Leung *et al.* (2020), calculates 'integrated information
25 structures' in fruit fly brains using electrocorticography (tiny elec-
26 trodes inserted such that they rest inside the head but on top of the fly
27 brains). The researchers concluded that their new measure of mecha-
28 nism-level (as opposed to global-level) phi was a better tool than the
29 simple scalar system-level phi value that is the key diagnostic tool of
30 IIT because it provided more than a scalar value to compare the
31 capacity for consciousness.
32   The approach taken by Leung *et al.* may, however, miss key
33 features of information integration because it doesn't measure global
34 EEG fields and their interactions, such as cross-frequency coupling or
35 harmonic coupling (a specialized case of maximal cross-frequency
36 coupling), focusing instead only on local field potential (LFP) and its
37 more localized electromagnetic field dynamics. A growing number of
38 theorists are suggesting that the brain's local and global electromag-
39 netic fields may be the primary seat of consciousness (e.g. Hales,

1   2014; Jones, 2013). Under this approach, then, we would look to these
2   field dynamics for our primary NCC and 'signatures of consciousness'.

3   *3.3. GRT adopts a process notion of the flow of time*

4   GRT adopts a process notion of time (Hunt, 2014; Whitehead, Griffin
5   and Sherburne, 1929). As described in Hunt (2014), this is a notion of
6   time that matches the human *experience* of time, which appears to
7   entail a steady passage of perceptual moments (Koch, 2004), and
8   resolves various difficulties presented by other notions of time. So,
9   while some observers may consider GRT's adoption of process time
10   to be a difficulty or limitation of the theory, this may be one of its
11   strengths.

12   **4. Conclusion**

13   The mathematical framework offered here may be useful to both
14   researchers and philosophers in probing the nature and extent of
15   consciousness. Various other quantification and characterization
16   approaches have been offered, including in particular the integrated
17   information theory developed by Tononi, Koch, and others. Hunt
18   (2011; 2014) describes how GRT and IIT differ and those differences
19   between the theories generally remain. I acknowledge in the present
20   paper that IIT's tools for characterizing phenomenal experience —
21   depiction of visual 'constellations' for each possible quale in a given
22   complex — rather than only quantifying the capacity for such experi-
23   ences, as is done in the present paper, may be compatible with GRT.
24   IIT's constellation-qualia characterization tools may help to fill in key
25   gaps with GRT.
26   The key difference between GRT and IIT is an explicitly process
27   view of time in GRT, and various types of shared resonance (and thus
28   various phase transitions in the transmission of information) forming,
29   consequently, the key signature of complex consciousness. IIT relies
30   instead on an 'exclusion principle' for defining the dominant con-
31   sciousness ('maximally irreducible conceptual structure' or MICS)
32   present in any collection of items (Oizumi, Albantakis and Tononi,
33   2014). GRT results in a nested hierarchy of conscious entities in any
34   complex consciousness, whereas IIT results in the extinction of sub-
35   sidiary conscious entities as a result of the combination of conscious-
36   ness into a single larger entity. Hunt (2014) describes these differ-
37   ences in more detail.

This is not the place for a detailed comparison between GRT and other theories of consciousness. However, GRT was developed as a way to mitigate at least some of the difficulties posed by other theories of consciousness. The approach proposed is also a relatively simple mathematical framework, and simplicity presents some advantages.

Acknowledgments

References

Bandyopadhyay, A. (2019) Resonance chains and new models of the neuron, *Medium.com*, 15 June, [Online], https://medium.com/@aramis720/resonance-chains-and-new-models-of-the-neuron-7dd82a5a7c3a.

Bahramisharif, A., Gerven, M.A., Aarnoutse, E.J., Mercier, M.R., Schwartz, T.H., Foxe, J.J., Ramsey, N.F & Jensen, O. (2013) Propagating neocortical gamma bursts are coordinated by traveling alpha waves, *Journal of Neuroscience*, **33** (48), pp. 18849–18854.

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

Chiang, C., Shivacharan, R., Wei, X., Gonzalez-Reyes, L. & Durand, D. (2019) Slow periodic activity in the longitudinal hippocampal slice can self-propagate non-synaptically by a mechanism consistent with ephaptic coupling, *Journal of Physiology*, **597** (1), pp. 249–269.

Craddock, T.J., Kurian, P., Preto, J., Sahu, K., Hameroff, S.R., Klobukowski, M. & Tuszynski, J.A. (2017) Anesthetic alterations of collective terahertz oscillations in tubulin correlate with clinical potency: Implications for anesthetic action and post-operative cognitive dysfunction, *Scientific Reports*, **7** (1), art. 9877.

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

Dehaene, S. (2014) *Consciousness and the Brain: Deciphering How the Brain Codes Our Thoughts*, London: Penguin.

Edelman, G.M. & Tononi, G. (2001) *A Universe of Consciousness: How Matter Becomes Imagination*, New York: Perseus Books.

Fries, P. (2005) A mechanism for cognitive dynamics: Neuronal communication through neuronal coherence, *Trends in Cognitive Sciences*, **9**, pp. 474–480.

Fries P. (2015) Rhythms for cognition: Communication through coherence, *Neuron*, **88** (1), pp. 220–235.

Gelperin, A. (2014) Comparative chemosensory cognition, *Frontiers in Behavioral Neuroscience*, **8**, art. 190.

Ghanbari, Z. & Moradi, M.H. (2020) FSIFT-PLV: An emerging phase synchrony index, *Biomedical Signal Processing and Control*, **57**, 101764.

Goff, P. (2017) *Consciousness and Fundamental Reality*, Oxford: Oxford University Press.

Grossberg, S. (2017) Towards solving the hard problem of consciousness: The varieties of brain resonances and the conscious experiences that they support, *Neural Networks*, **87**, pp. 38–95.

Hahn, G., Bujan, A.F., Frégnac, Y., Aertsen, A. & Kumar, A. (2014) Communication through resonance in spiking neuronal networks, *PLoS Computational Biology*, **10** (8), e1003811.

Hales, C.G. (2014) The origins of the brain's endogenous electromagnetic field and its relationship to provision of consciousness, *Journal of Integrative Neuroscience*, **13** (02), pp. 313–361.

Hameroff, S.R. (2009) The 'conscious pilot' — dendritic synchrony moves through the brain to mediate consciousness, *Journal of Biological Physics*, **36** (1), pp. 71–93.

Hameroff, S. & Penrose, R. (2014) Consciousness in the universe: A review of the 'Orch OR' theory, *Physics of Life Reviews*, **11** (2014), pp. 39–78.

Hardie, R.C. & Raghu, P. (2001) Visual transduction in drosophila, *Nature*, **413** (6852), pp. 186–193.

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

Hunt, T. (2014) *Eco, Ego, Eros: Essays on Philosophy, Spirituality and Science*, Santa Barbara, CA: Aramis Press.

Hunt, T. (2019a) Resonance and process philosophy, *Medium.com*, 10 June, [Online], https://medium.com/@aramis720/resonance-and-process-philosophy-e5b801045ca6.

Hunt, T. (2019b) How can you tell if another person, animal, or thing is conscious: Try these 3 tests, *theconversation.com*, 1 July, [Online], https://theconversation.com/drafts/115835/edit.

Hunt, T. (2020) *The Feeling of Life Itself*: A conversation with Christof Koch about his new book and latest reflections on the science of consciousness, *medium.com*, [Online], https://tamhunt.medium.com/the-feeling-of-life-itself-7747eed82944.

Hunt, T. & Schooler, J. (2019) The 'easy part' of the hard problem: A resonance theory of consciousness, *Frontiers in Human Neuroscience*, **13**, art. 378.

Hunt, T., Ericson, M. & Schooler, J.W. (ms) Where's my consciousness-ometer? in progress.

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

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

Klimesch, W. (2018) The frequency architecture of brain and brain body oscillations: An analysis, *European Journal of Neuroscience*, **48**, pp. 2431–2453.

Koch, C. (2004) *The Quest for Consciousness: A Neurobiological Approach*, London: Roberts Publishers.

Koch, C. (2019) *The Feeling of Life Itself: Why Consciousness is Widespread but Can't Be Computed*, Cambridge, MA: MIT Press.

Lachaux, J., Rodriguez, E., Martinerie, J. & Varela, F.J. (1999) Measuring phase synchrony in brain signals, *Human Brain Mapping*, **8** (4), pp. 194–208.

Leung, A., Cohen, D., Swinderen, B.V. & Tsuchiya, N. (2020) Integrated information structure collapses with anesthetic loss of conscious arousal in Drosophila melanogaster, *bioRxiv*, [Online], https://doi.org/10.1101/2020.05.17.090001.

Maier, N., Nimmrich, V. & Draguhn, A. (2003) Cellular and network mechanisms underlying spontaneous sharp wave-ripple complexes in mouse hippocampal slices, *Journal of Physiology*, **550** (Pt 3), pp. 873–887.

Nunez, P.L. & Srinivasan, R. (2010) Scale and frequency chauvinism in brain dynamics: Too much emphasis on gamma band oscillations, *Brain Structure and Function*, **215** (2), pp. 67–71.

Oizumi, M., Albantakis, L. & Tononi, G. (2014) From the phenomenology to the mechanisms of consciousness: Integrated information theory 3.0, *PLoS Computational Biology*, **10** (5), [Online], https://doi.org/10.1371/journal.pcbi.1003588.

Qiu, C., Shivacharan, R.S., Zhang, M. & Durand, D.M. (2015) Can neural activity propagate by endogenous electrical field?, *Journal of Neuroscience*, **35**, pp. 15800–15811.

Rein, K., Zockler, M., Mader, M.T., Grubel, C. & Heisenberg, M. (2002) The drosophila standard brain, *Current Biology*, **12** (3), pp. 227–231.

Rodriguez-Larios, J. & Alaerts, K. (2019) Tracking transient changes in the neural frequency architecture: Harmonic relationships between theta and alpha peaks facilitate cognitive performance, *Journal of Neuroscience*, **39** (32), pp. 6291–6298.

Salart, D., Baas, A., van Houwelingen, J.A.W., Gisin, N. & Zbinden, H. (2008) Spacelike separation in a Bell test assuming gravitationally induced collapses, *Physical Review Letters*, **100** (22), pp. 1–4.

Schooler, J.W., Hunt, T. & Schooler, J.N. (2011) Reconsidering the metaphysics of science from the inside out, in Walach, H., Schmidt, S. & Jonas W. (eds.) *Neuroscience, Consciousness and Spirituality: Studies in Neuroscience, Consciousness and Spirituality*, vol. 1, Dordrecht: Springer.

Siebenhühner, F., Wang, S.H., Arnulfo, G., Lampinen, A., Nobili, L., Palva, J.M. & Palva, S. (2020) Genuine cross-frequency coupling networks in human resting-state electrophysiological recordings, *PLoS Biology*, **18** (5), e3000685.

Siegel, A., Sapru, H.N. & Siegel, H. (2019) *Essential Neuroscience*, Philadelphia, PA: Wolters Kluwer.

Takahashi, K., Saleh, M., Penn, R.D. & Hatsopoulos, N.G. (2011) Propagating waves in human motor cortex, *Frontiers in Human Neuroscience*, **5**, art. 40.

Tononi, G. & Koch, C. (2015) Consciousness: Here, there and everywhere?, *Philosophical Transactions of the Royal Society B*, **370**, 20140167.

Vallverdú, J., Castro, O., Mayne, R., Talanov, M., Levin, M., Baluška, F., Gunji, Y., Dussutour, A., Zenil, H. & Adamatzky, A. (2018) Slime mould: The fundamental mechanisms of biological cognition, *Biosystems*, **165**, pp. 57–70.

Varela, F., Lachaux, J., Rodriguez, E. & Martinerie, J. (2001) The brainweb: Phase synchronization and large-scale integration, *Nature Reviews Neuroscience*, **2** (4), pp. 229–239.

Walleczek, J. (2000) *Self-Organized Biological Dynamics & Nonlinear Control: Toward Understanding Complexity, Chaos, and Emergent Function in Living Systems*, Cambridge: Cambridge University Press.

Whitehead, A.N., Griffin, D.R. & Sherburne, D.W. (1929) *Process and Reality: An Essay in Cosmology*, New York: Free Press.

Zhang, H. & Jacobs, J. (2015) Traveling theta waves in the human hippocampus, *Journal of Neuroscience*, **35** (36), pp. 12477–12487.