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Research Article

# About the compatibility between the perturbational complexity index and the global neuronal workspace theory of consciousness

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## Abstract

**This paper investigates the compatibility between the theoretical framework of the global neuronal workspace theory (GNWT) of conscious processing and the perturbational complexity index (PCI). Even if it has been introduced within the framework of a concurrent theory (i.e. Integrated Information Theory), PCI appears, in principle, compatible with the main tenet of GNWT, which is a conscious process that depends on a long-range connection between different cortical regions, more specifically on the amplification, global propagation, and integration of brain signals. Notwithstanding this basic compatibility, a number of limited compatibilities and apparent differences emerge. This paper starts from the description of brain complexity, a notion that is crucial for PCI, to then summary of the main features of PCI and the main tenets of GNWT. Against this background, the text explores the compatibility between PCI and GNWT. It concludes that GNWT and PCI are fundamentally compatible, even though there are some partial disagreements and some points to further examine.**

**Keywords:** perturbational complexity index; global neuronal worskpace theory; brain complexity; theory of consciousness; measurement of consciousness

## Introduction

### Brain complexity: definition and clinical relevance

Brain "complexity" has increasingly gained traction in consciousness research as a notion considered useful for advancing in the explanation and the clinical detection of conscious activity. Its original formalization in explicit relation to consciousness dates back to 1998, when Giulio Tononi and Gerald Edelman published the paper "Consciousness and Complexity" (Tononi and Edelman 1998).

To properly evaluate the explanatory value of complexity for consciousness, it is crucial to first clarify the meaning of both terms. In fact, complexity is so general to seem meaning different things in different contexts and in different disciplines (Adami 2002). One is simply that we qualify complex "an organization or a system that we don't understand and master" (Thom 1990). For this reason, the concept of complexity is applicable to life, in general, rather than to consciousness only. Similarly, consciousness may assume different specific meanings. For instance, in the clinical context, there is a distinction between the level (or state) of consciousness (i.e. wakefulness/sleep) and its content (e.g. images or words) (Laureys 2005). For the sake of our analysis, we assume levels and contents as two distinct but not completely dissociable dimensions (Bachmann and Hudetz 2014; Mashour, et al. 2020).

Another popular distinction, even though not unanimously accepted (Naccache 2018), has been introduced by Ned Block, who differentiated phenomenal consciousness (i.e. subjective experience or "what it is like to be") from access consciousness (i.e. availability of information for use in reasoning and rationally guiding speech and action) (Block 1995). Given the multiple meanings that both terms can assume, it is important to disambiguate them. Namely, the term consciousness should not be used without specifying it, for instance, if referred to conscious processing of specific contents, to conscious access, or to the state of consciousness. We will see in the following that some apparent disagreements between different theories arise from the fact that they refer to different meanings of consciousness (e.g. content rather than state).

In the paper referred earlier, Tononi and Edelman try "to characterize the kinds of neural processes that might account for key properties of conscious experience" (Tononi and Edelman 1998). Thus, they conceive consciousness as subjective experience. The key properties the authors identify are "integration" (i.e. conscious

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experience is unified) and "differentiation" (i.e. one can experience any of a large number of different conscious states and/or contents). On the basis of them, Tononi and Edelman provide a technical definition of complexity conceived to include both "functional integration and functional specialization or segregation" (i.e. differentiation). This definition of complexity is usually assumed, implicitly or explicitly, in subsequent research on consciousness, especially in the clinical context.

This is clearly illustrated in a recent systematic review of the use of complexity in the context of consciousness research (Sarasso, et al. 2021). The authors outline that measures of complexity (understood as integration + differentiation) have been increasingly used in the last 15 years, with a significant increase in the last 2 years, to index changes in the "state" of consciousness in different conditions (e.g. rapid eye movement (REM) and non-rapid eye movement sleep, general anesthesia, altered states of consciousness, epilepsy, coma, and disorders of consciousness (DoCs)).

The same understanding of complexity is reflected in a recent article, which proposed a more technical operationalization of complexity as "a pattern of positive and negative long-distance coordination, high modularity, with low similarity to the anatomical connectivity potentially relevant for the support of conscious cognition"(Demertzi, et al. 2019). This definition relates complexity to the integration (i.e. long-distance coordination) of different brain areas and to the differentiation of functional modules and importantly specifies that the functional organization of a complex pattern does not reflect the underlying anatomical connectivity. This latter point suggests the possibility that between function (i.e. as recorded by electrophysiological methods and/or brain imaging) and structure of a complex system (i.e. neuronal connectivity), there is not a one-to-one correspondence.

Importantly, the notion of complexity is usually referred to the "level/state" of consciousness rather than to its "contents." This means that complexity-related measures can provide relevant information about the "level/state" of consciousness, while they are silent about the corresponding object as well as its phenomenology. Actually proponents of integrated information theory (IIT) have recently attempted to articulate a connection between complexity and the phenomenology of conscious experience, namely, the experience of spatial extendness (Haun and Tononi 2019), but these attempts are admitted at a very initial stage and in need of further development (Tononi, et al. 2022). Thus far, complexity-based theories, like IIT, have provided testable predictions targeting only the level/state of consciousness (Seth, et al. 2011). In fact, measures of complexity are interpreted as quantitative aspects of consciousness, i.e., as targeting its states, without any reference to its content. Thus, IIT starts from phenomenology, which should include a reference to conscious contents, but it eventually ends up in providing quantifiable measures to assess the level/state of consciousness (Koculak and Wierzchon 2022). In fact, theoretically IIT defines the content of consciousness as the shape of its conceptual (i.e. cause–effect) structure, but no way for quantifying it is described so far, notwithstanding relevant attempts currently in progress (Haun and Tononi 2019; Albantakis, et al. 2023).

Provided this specification, complexity measures seem to show a higher sensitivity to the state of consciousness than other alternative measures, like event-related potentials (e.g. P3b), measures based on global metabolic rates, and global spectral measures. As recently outlined, all the complexity-related metrics "concurred on the same conclusion: complexity is higher in conditions in which consciousness is present and lower in conditions where this is lost" (Sarasso, et al. 2021). In short, complexity-related measures seem to outperform other approaches in both sensitivity (i.e. true positive rate) and specificity (i.e. true negative rate), as confirmed in a number of studies (Casali, et al. 2013; Sitt, et al. 2014; Casarotto, et al. 2016; Demertzi, et al. 2019; Luppi, et al. 2019). This kind of measure of the brain's capacity for conscious states is particularly useful in the clinical treatment of unresponsive patients with severe brain injuries, which may be still conscious but actually disconnected from the outside (i.e. unable to perceive external stimulation as well as to behave) (Massimini, et al. 2009). Accordingly, the clinical value of complexity-related measures has been recognized in recent international guidelines on DoCs (Giacino, et al. 2018; Kondziella, et al. 2020).

## Main features of perturbational complexity index

On the basis of the notion of brain complexity as summarized earlier, a methodology for measuring it has been developed and clinically validated. It basically consists in using transcranial magnetic stimulation (TMS) in combination with electroencephalogram (EEG), which allows us to monitor cortico-cortical interactions on a millisecond timescale (Massimini, et al. 2009). Selected cortical regions are stimulated with TMS, and then their response and the eventual interaction with other regions are monitored and quantified. The cortical responses to TMS have been found to be significantly different between conscious and non-conscious states, in a way that is dependent on the actual level of consciousness (e.g. healthy conditions, anesthetized subjects, and patients with DoCs) (Massimini, et al. 2005, 2010; Ferrarelli, et al. 2010; Rosanova, et al. 2012; Sarasso, et al. 2015). Thus, the cortical response to TMS has been interpreted as an "index" of the level of consciousness, which has been formalized in an algorithm, called perturbational complexity index (PCI), which basically measures the ability of "functionally specialized modules of the thalamocortical system to interact rapidly and effectively thus producing complex patterns of activity" (Casali, et al. 2013). In short, four steps are necessary to measure PCI: perturbing the brain; recording cortical response to perturbation; statistically extracting a binary matrix describing the spatio-temporal pattern of deterministic, causal interactions; and compressing this matrix (Casali, et al. 2013). The more this matrix can be compressed, the lower the brain complexity and then the PCI, which basically reflects how many distant cortical areas are activated in a non-stereotypical way (e.g. at different timescales).

PCI has also been scaled in relation to different states of consciousness, and a cut-off between conscious and non-conscious states is identified at 0.31, a value that is called PCI* (Casali, et al. 2013). The clinical validation of this threshold revealed its ability to discriminate between different DoCs [namely, vegetative state/unresponsive wakefulness syndrome (VS/UWS), and minimally conscious state (MCS)], showing higher sensitivity and specificity than behavioral diagnostic tools (Casarotto, et al. 2016). This is illustrated, for instance, by the case of a patient with an initial diagnosis of VS/UWS that gradually recovered consciousness up to the state of MCS. The level of complexity as indexed by PCI reached a value compatible with the diagnosis of MCS about 10 days before than the behavioral assessment showed the new state (Rosanova, et al. 2012). This also illustrates the potential prognostic value of PCI.

## Main tenets of the GNWT

The idea of a cognitive global workspace (GW) was originally introduced by the psychologist Bernard Baars (Baars 1988): specialized, non-conscious processors operating in parallel compete for access to a limited system, called GW, which allows the processors to exchange information (Bayne, et al. 2009). In this model, the actual content of consciousness corresponds to what is in the GW.

Dehaene, Kerszberg, and Changeux introduced a neurobiological basis to the GW referred to as the GNWT of consciousness (Dehaene, et al. 1998). Its main postulate is that "conscious access corresponds to global information availability": "what we subjectively experience as conscious access is the selection, amplification and global broadcasting, to many distant areas, of a single piece of information selected for its salience or relevance to current goals" (Dehaene, et al. 2011), which would be mediated by a defined network of long-range connectivity.

The aim of GNWT is to model the independent processing of several and different signals passing through distinct parallel pathways and their integration in a unified physical field or a common workspace (Changeux 2004).

Neuronally, Dehaene, et al. (2011) distinguish two distinct computational spaces within the brain: a processing network, composed of a set of parallel, distributed, and functionally specialized processors (Baars 1988) or modular subsystems (Shallice 1988) and a global neuronal workspace (GNW).

Anatomically, the definition of GNW by Dehaene, Kerszberg, and Changeux is different from Baars' GW: while this is limited to the brainstem and to non-specific thalamic nuclei, the first identified GNW with a system relying on cortical pyramidal neurons with long-distance cortico-cortical and subcortical connections, which can broadcast signals at the brain scale (Dehaene, et al. 1998). Thus, according to Dehaene, Kerszberg, and Changeux, GNW covers different cortical regions, even though pyramidal cells can be denser in specific areas. Yet it is always "vertically" interconnected with their thalamic counterpart. Recently, for evolutionary reasons, the cerebellum has been included in the GNW (Hublin and Changeux 2022). Consequently, there is no particular cerebral area where conscious processing is located, but a brain-scale process of conscious synthesis is achieved when multiple processors converge to a coherent metastable state (Dehaene, et al. 2011; Mashour, et al. 2020).

In short, GNWT suggests that a subset of cortical pyramidal cells with long-range excitatory axons, particularly dense in prefrontal, parieto-temporal, and cingulate regions, together with the relevant thalamocortical loops, form a "horizontal" neuronal workspace interconnecting the multiple specialized, automatic, and non-conscious processors (Dehaene and Changeux 2011). The difference between conscious and non-conscious representation (which is an organized activity pattern) is that while this is encapsulated within discrete processors, conscious representation is globally broadcasted within the GNW as a physiological process referred to as "ignition" (Dehaene, et al. 2005). In this way, the representation is processed and can be verbally reported (but conscious access can be dissociated from reportability (Mashour, et al. 2020). In the end, what we experience as a conscious state is global availability of information (Dehaene and Naccache 2001).

Specifically, the following five sets of brain systems have been identified as constituting GNW (Bayne, et al. 2009): high-level perceptual processors (e.g. inferotemporal cortex), evaluation circuits (e.g. amygdala, cingulate, and orbitofrontal regions), planning and motor intention systems (e.g. prefrontal and premotor areas), long-term memory circuits (e.g. hippocampus and parahippocampal regions), and attention-orienting circuits (e.g. posterior parietal cortices). According to GNWT, these areas interconnect to form a higher-level unified space where representation is broadly shared and broadcasted (Dehaene, et al. 2011).

Moreover, it has been possible to identify the following properties of GNW architecture through its simulation (Dehaene, et al. 2005; Bayne, et al. 2009):

(i) Feedforward excitation followed by ignition: Processing of external stimuli has two stages: first, an ascending feedforward bottom-up propagation of the stimulus up to cortical areas and then a top-down amplification and maintenance by a fraction of GNW neurons (Dehaene, et al. 2011).
(ii) Central competition and inhibition: Each ignition activates a subset of thalamocortical columns, while the rest of workspace is inhibited. This means that other stimuli cannot enter GNW. It also underlines the importance if inhibition in conscious processing (Volzhenin, et al. 2022).
(iii) All-or-none ignition: Ignition corresponds to a quick dynamic burst of activity (eventually referred to as phase transition), so that a stimulus either fully ignites GNW or its activation quickly dies out.
(iv) Oscillations and synchrony: Ignition increases membrane voltage oscillations and synchrony between distant cortical areas.
(v) Stochasticity: Conscious access is stochastic and depends on spontaneous activity that determines what surpasses ignition threshold.
(vi) Subliminal versus preconscious states: When the stimulus is too weak, its bottom-up activation does not last enough to activate GNW and the stimulus is subliminal. If the stimulus has enough strength, it could anyway not activate GNW if this is already occupied by a competing conscious representation. Consequently, the stimulus is preconscious.
(vii) Graded levels of vigilance: The ignition threshold is affected by ascending neuromodulation corresponding to a gradation of states of consciousness.
(viii) Spontaneous activity: An ongoing spontaneous activity characterizes GNW, where spontaneous ignitions originate endogenously (Dehaene, et al. 2005). This means that global ignited states, i.e. conscious access, can occur independent of external stimulation. In this case, activation starts in high-level areas and is propagated top-down.

Moreover, considerable empirical data confirm the GNW prediction that pre-stimulus baseline fluctuations partially predict conscious perception: a stimulus can access conscious processing or not depend on its exact phase relative to the ongoing spontaneous activity (Dehaene, et al. 2011). This has also been recently indicated by the data collected by another group and their theoretical interpretation (Rabuffo, et al. 2022).

The above-mentioned properties of GNW architecture are also relevant for assessing residual conscious activity in DoCs. In fact, defining a local-global paradigm (Bekinschtein, et al. 2009; Faugeras, et al. 2012; King, et al. 2013), GNWT indicates signatures of conscious processing that could potentially be used in clinical contexts to infer and even to assess residual conscious access in patients with DoCs:

(a) Amplification of the signal and access to prefrontal–parietal–cingulate cortices.
(b) Late global ignition and metastability: While a non-conscious stimulus is only locally processed (for instance, an unconscious image processed in the visual cortex), a

conscious stimulus is propagated in higher cortical areas in a non-linear manner, according to a phenomenon called "global ignition." Particularly, brain activity becomes more stable after around 200–300 milliseconds if the stimulus is conscious (Schurger, et al. 2015; Mashour, et al. 2020). Importantly, this marker of conscious processing has not been associated with a quantification of information/differentiation so far, and it is often absent in conscious conditions in which stimuli are not task relevant (Pitts, et al. 2014; Sergent, et al. 2021).[1] Both points deserve further research.

(ix) Brain-scale diffusion of representation: When a stimulus is consciously processed, there is a correlation of brain signals within the cortex involving its parts at greater distances than what happens with non-conscious stimuli.
(x) Global spontaneous activity: In the absence of external stimuli, the brain is always spontaneously active. This intrinsic activity is highly relevant for consciousness, since the time and modality of their interaction affect the content of the latter (Dehaene, et al. 2005).
(xi) Late all-or-none firing of "concept cells": As reported in Quiroga, et al. (2008), it has been possible to identify specific neurons in prefrontal and anterior temporal cortices that fire to specific concepts. This means that their late activity can be assumed as a signature of consciousness.

Moreover, GNWT predicts that patients with DoCs, specifically patients in coma and VS/UWS, retain the initial stages of processing external stimuli but not the late stages. This has been confirmed by functional Magnetic Resonance Imaging activation and Positron Emission Thomography studies with patients in VS/UWS, showing the persistence of post-stimulus activation of brainstem, thalamus, and primary somatosensory cortex (Laureys, et al. 2002; Tshibanda, et al. 2010), while the sensory areas are functionally disconnected from "higher-order" associative multimodal areas (Laureys, et al. 2002; Boly, et al. 2005).

Finally, the clinical relevance of GNWT for exploring DoCs is especially related to its prediction that improvements of DoCs depend on the reactivation of long-distance prefrontal and parietal networks, as confirmed by empirical studies on VS/UWS (Laureys, et al. 2000).

## Discussion

### How much compatible are PCI and GNWT?

The compatibility between PCI and GNWT depends on the level of details considered (Table 1).

Overall, results derived from the application of TMS-EEG as summarized in PCI are compatible with GNWT. In fact, for both PCI and GNWT, conscious state is relates to a "deeper and more prolonged propagation of activation through long-distance connections compared to the unconscious state" (Mashour, et al. 2020). In a recent attempt to revisiting the GW orchestrating the hierarchical organization of the brain, Deco et al. (2021) have introduced the notion of "functional rich club" to indicate "the core set of regions, an array of functional hubs that are characterized by a tendency to be more densely functionally connected among themselves than to other brain regions from where they receive integrative information" (Deco, et al. 2021). Accordingly, integration can be defined as the maximization of inter-modular communication (e.g. functional rich club or efficient communication) and the reduction of clustering or modularity (Wajnerman Paz 2022). Thus, there is a basic compatibility between GNWT and PCI as both relate the conscious state to sustained long-distance cortical connections. In a nutshell, for GNWT, the state of consciousness is related to the brain's capacity to sustain prolonged propagation of activation (i.e. a global broadcasting of representation) to long-distance prefrontal and parietal networks. It is plausible, if not probable, that this kind of broadcasting is associated with high spatio-temporal complexity in response to an external perturbation (i.e. high PCI). At the same time, it is also plausible, if not probable, that high spatio-temporal complexity in response to a cortical perturbation (i.e. high PCI) might depend on the integrity and availability of the same networks. Therefore, the results of PCI may well be strictly compatible with the GNWT predictions.

If we focus on more specific aspects, a number of differences emerge, which do not necessarily indicate incompatibility between PCI and GNWT but either partial compatibilities or the necessity/opportunity to further check their compatibility, namely, through an empirical exploration of the relevance of PCI to assess conscious contents in addition to conscious states.

A first difference is in the background definition of consciousness and in the identification of related neuronal structures. For both theoretical and experimental reasons, GNWT has been originally limited to conscious access. Therefore, for GNWT, a conscious process corresponds to global access of representation by different specialized processors. More specifically, a top-down representation flow as selection and broadcasting of signal to specialized sensory processors and thalamocortical loops is crucial for conscious processing (Mashour, et al. 2020). This is the reason why conscious access is not attached to early sensory processing, while ignition as a sudden, strong, and sustained activity discriminates between conscious and non-conscious processing. Concerning the neuronal structures involved in conscious processing, as seen earlier, for GNWT, the frontal cortex with its long-distance fiber tracts plays an important role in sustaining long-range functional connectivity in networks supporting the GNW and therefore conscious access (Mashour, et al. 2020). Yet, this does not imply that only cortical activity is involved in conscious access: in fact, subcortical layers are also recruited, particularly the thalamus, as confirmed by Afrasiabi et al. (2021), which show the contribution of subcortical areas (i.e. thalamus and striatum) to decode conscious states and to integrate neuronal activity patterns during conscious access (Afrasiabi, et al. 2021).

PCI relies on a background definition of consciousness as a conscious state. More specifically, the conscious state is indexed by integrated and differentiated information. As mentioned earlier, PCI has been introduced within the framework of IIT, but the relation between them is contested. Virmani and Nagaraj (2019) outline that PCI lacks a theoretical clear link with IIT, so that the first cannot be used to confirm the second (Virmani and Nagaraj 2019). In fact, as seen earlier, the concept of brain complexity is flexible enough to accommodate different theoretical models of consciousness, conceived as both conscious access to information and conscious state. Therefore, as argued by Koculak and Wierzchon (2022), it is mistaken to identify complexity with IIT, as well as limiting the relevance of complexity to the states of consciousness excluding any reference to its contents (Koculak and Wierzchon 2022).

Notwithstanding its original focus on conscious access, GNWT is relevant for getting relevant information from brain dynamics about both the level (or state) and the content of consciousness.

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[1] We thank an anonymous reviewer for highlighting this point.

**Table 1.** Points that are compatible, partially and/or in principle compatible, not compatible, and to be checked

| Compatible | |
|---|---|
| Conscious state is related to deep and prolonged propagation of organized neuronal activity through long-distance connections | |
| Partially and/or in principle compatible | |
| GNWT | PCI |
| It targets the "level/state" and the "content" of a conscious process | It targets the "level/state" of a conscious process |
| A subset of GNW neurons may be activated by external stimuli, cognitive task, or stochastically by spontaneous activity | PCI results from externally triggered brain activation. It is as such silent about conscious states activated by cognitive tasks or by stochastic spontaneous brain activity but, in principle, not incompatible with them |
| Not compatible | |
| GNWT | PCI |
| A crucial role for a conscious state is played by the GNW and by fronto-parietal cingulate networks as part of it, particularly through distributed excitatory neurons with long-range axons able to receive organized neuronal signals from and broadcast them to local processors through reciprocally connecting tracts | It focuses on the "cause–effect structure" of the interaction between different specialized modules, without identifying any specific area critical for the conscious state |
| Conscious access and state depend on top-down broadcasting of the organized neuronal activity pattern and on recurrent loops between lower and higher cortical areas ("feedforward" and "feedback" connections) | A conscious state correlates with the number of long-distance cortical regions activated by the input ("integration") and the amount of "differentiation" among them. PCI does not mention top-down broadcasting of neuronal activity |
| To be checked | |
| GNWT | PCI |
| A conscious process, including conscious state, corresponds to "global access of information" (i.e. representation or organized neuronal activity pattern) by different specialized processors | A "conscious state" corresponds to "integrated and differentiated information" |
| Anti-correlated activity between different brain regions (accessing the GNW at different times) | |
| Conscious access is different from the perceptual report | |
| Representational in nature | |
| | The level of conscious processing can be quantified |
| The signal broadcasting which according to GNWT is crucial for conscious state may be associated with high spatio-temporal complexity in response to an external perturbation (i.e. high PCI)[1] | High spatio-temporal complexity in response to a cortical perturbation (i.e. high PCI) might depend on the integrity and availability of the same networks crucial for signal broadcasting[1] |
| The brain areas (e.g. prefrontal cortex) and processes (e.g. top-down pathways) identified by GNWT as critical for conscious access and state may play a crucial role in achieving the brain complexity measured by PCI | |

[1] We thank an anonymous reviewer for highlighting this point.

PCI provides an estimate of the level/state of consciousness, while it is silent about its possible content. While, at present, PCI has been validated only as a measure of the state of consciousness, the question is open whether it may be extended to also monitor the capacity for conscious processing of specific information. For the time being, on this specific aspect, GNWT and PCI are only in part compatible (i.e. concerning the state of consciousness) and potentially compatible (i.e. concerning the content of consciousness).

Another point on which PCI and GNWT appear only in part compatible is that while for GNWT, a conscious process, including both conscious access and state, may be initiated by external stimuli, a cognitive task, or stochastically by spontaneous brain activity, PCI results from externally triggered brain activation: it is true that the stimulus employed to test the brain's capacity for consciousness does not need to be consciously perceived to quantify the PCI, but this eventually measures the effect of an externally triggered stimulus Thus, PCI is not calibrated on conscious states activated by intrinsic cognitive tasks or by stochastic spontaneous brain activity, even if, in principle, PCI is not incompatible with them. This is another aspect that may be further explored.

PCI and GNWT appear incompatible in relation to a number of points. First, as summarized earlier, according to GNWT, a crucial role for a conscious process is played by the GNW and by fronto-parietal-cingulate networks as part of it, particularly through distributed excitatory neurons with long-range axons able to receive organized neuronal signals from and broadcast them to local processors through reciprocally connecting tracts. As seen earlier, GNWT does not ignore the role played by other brain regions, including subcortical structures, for conscious processing, but the prefrontal cortex is considered a basic constitutive component for advanced conscious processing and meta-awareness, including reportability. PCI focuses instead on the cause–effect structure of the interaction between different specialized modules, without identifying any specific critical area or network for conscious processing, including posterior cortical territories.

Second, for GNWT of consciousness, access depends on top-down broadcasting of neuronal activity patterns and on recurrent loops between lower and higher cortical areas (feedforward and feedback connections). For PCI, conscious process correlates with the number of long-distance cortical regions activated by the input (integration) and the amount of differentiation among them rather than with top-down broadcasting of information.

It is possible that these incompatibilities are not irreducible but rather depend on the state-of-the-art of consciousness science, affected by both theoretical and technical limitations. Specifically, it is possible that the brain areas (e.g. prefrontal cortex) and processes (e.g. top-down pathways) identified by GNWT as critical for conscious access and state also play a crucial role in achieving the brain complexity measured by PCI.[2]

There are then some aspects that need to be better explored in order to check the actual compatibility between PCI and GNWT. Among them, GNWT is representational in nature, because it targets the content of consciousness, while in its current form, PCI does not refer to the representational capacity of the brain. Also, according to PCI, the state of consciousness can be quantified (as the level of complexity), while the global ignition as a central mechanism for GNWT seems to suggest an all-or-none phenomenon of conscious processing.

## What does the compatibility between PCI and GNWT mean?

The fact that a theoretical model of consciousness, specifically GNWT, is retrospectively (at least in part) compatible with PCI does not mean that the latter can be assumed in support of the validity of the former. This (at least partial) compatibility is rather evidence of the need to explore the theoretical relevance of an empirical index like PCI within different and even concurrent theories than IIT, not for validating them but for possibly providing them with refined or new empirical tools for assessing consciousness.

Historically, the ideas proposed by Tononi and Edelman have been expressed earlier by Henri Atlan, who applied integrated information to living organisms in general and consequently to consciousness in particular (Atlan and Fessard 1972; Atlan 1979). The connections between Atlan's perspective and IIT deserve to be explored further. Also, theoretical antecedents to IIT are expressed in previous work by Gerald Edelman, including the remark that an exclusive focus on functions ignoring the physical structure cannot explain consciousness (Edelman 1989). Anyway, it is true that, as we highlighted earlier, the relationship between consciousness and brain complexity has been formalized by Tononi and Edelman and subsequently systematized within the IIT framework, particularly as part of what has been recently described as "weak IIT" (i.e. the search for empirically measurable correlates of different aspects of consciousness) (Mediano, et al. 2022). These theoretical approaches predicted that reliable measures of the state of consciousness should quantify both integration and differentiation (i.e. complexity), while GNWT has usually focused only on one of these two components (i.e. on integration understood as broadcasting of representation, i.e. organized neuronal activity pattern). This is mainly due to the fact that, as mentioned earlier, the target of GNWT has been limited to conscious access. Yet, the original formulation of GNWT also included reference to diversification. In fact, GNW cannot be reduced to a passive processor of representations, and GNWT is accordingly not limited to integration, but it also includes diversification though the combination of representations and importantly of rewards to selected representations (Dehaene, et al. 1998). This is made possible by evaluation circuits that allow representations in the GNW to be associated with positive or negative value. In this way, conscious representation is not reduced to the integration of incoming stimuli, but it is the result of a "generator of diversity" (Dehaene, et al. 1998), which constantly projects and tests hypotheses on the outside world (Dehaene and Changeux 1991, 1997). Therefore, GNWT as originally conceived also includes the recognition of the second component of brain complexity (i.e. differentiation). The relevance of GNWT to differentiation has been empirically confirmed by more recent data from studies about anesthesia and DoCs. Anesthetics like propofol, sevoflurane, and ketamine alter the functional relationship between critical nodes in the GNW, and so they impact the integration of these GNW components. At the same time, these anesthetics also reduce the dynamic diversity of functional connectivity patterns and so they impact the differentiation of these patterns, which become more constrained by anatomy, as also observed in DoCs (Barttfeld, et al. 2015; Demertzi, et al. 2019).

In short, we do not interpret the (at least partial) compatibility between PCI and GNWT as a kind of *post hoc* evidence of the validity of GNWT, but, on the one hand, as indicating that the theoretical framework of GNWT is open to further refinement (specifically in order to accommodate new data about both conscious access and conscious state), possibly rediscovering and elaborating some elements from its original formulation that have been subsequently ignored, and, on the other hand, as raising the need to explore the possibility of extending PCI to also conscious access and contents.

## Conclusion

There is a fundamental compatibility between GNWT and PCI: for both, a conscious state is related to deep and prolonged propagation of organized neuronal activity through long-distance connections. Against this background compatibility, there are a number of partial compatibilities, disagreements, and points to further explore. It is possible that apparent incompatibilities depend on the state-of-the-art of consciousness science and will be solved in the future. In particular, the possibility to extend PCI to conscious contents in addition to conscious state should be empirically explored.

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## Conflict of interest statement

None declared.

## Data availability

There are no original data linked to the paper.

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