Information Closure Theory of Consciousness

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Contents

Abstract

Information processing in neural systems can be described and analysed at multiple spatiotemporal scales. Generally, information at lower levels is more fine-grained and can be

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coarse-grained in higher levels. However, information processed only at specific scales of coarse-graining seems to be available for conscious awareness. We do not have direct experience of information available at the scale of individual neurons, which is noisy and highly stochastic. Neither do we have experience of more macro-scale interactions such as interpersonal communications. Neurophysiological evidence suggests that conscious experiences co-vary with information encoded in coarse-grained neural states such as the firing pattern of a population of neurons. In this article, we introduce a new informational theory of consciousness: Information Closure Theory of Consciousness (ICT). We hypothesise that conscious processes are processes which form non-trivial informational closure (NTIC) with respect to the environment at certain coarse-grained scales. This hypothesis implies that conscious experience is confined due to informational closure from conscious processing to other coarse-grained scales. ICT proposes new quantitative definitions of both conscious content and conscious level. With the parsimonious definitions and a hypothesise, ICT provides explanations and predictions of various phenomena associated with consciousness. The implications of ICT naturally reconciles issues in many existing theories of consciousness and provides explanations for many of our intuitions about consciousness. Most importantly, ICT demonstrates that information can be the common language between consciousness and physical reality.

Keywords:

Keywords: theory of consciousness, non-trivial informational closure, NTIC, coarse-graining, level of analysis

1 Introduction

Imagine you are a neuron in Alice's brain. Your daily work is to collect neurotransmitters through dendrites from other neurons, accumulate membrane potential, and finally send signals to other neurons through action potentials along axons. However, you have no idea that you are one of the neurons in Alice's supplementary motor area and involved in many motor control processes for Alice's actions, for example, grabbing a cup. You are ignorant of intentions, goals, and motor plans that Alice has at every moment even though you are part of the physiological substrate responsible for all those actions. A similar story also happens to Alice's conscious mind. To grab a cup, for example, Alice is conscious of her intention and visuosensory experience of this action. However, her conscious experience does not reflect the dynamic of your membrane potential or the action potentials you send to other neurons every second. That is, not all information you have is available to Alice's conscious mind.

It seems to be true that we are not consciously accessing information processed at every scale in the neural system. There are both more microscopic and more macroscopic scales than the scale corresponding to the conscious contents. On the one hand, dynamics of individual neurons are stochastic (Goldwyn & Shea-Brown, 2011; White *et al.*, 2000). However, what we are aware of in our conscious mind shows astonishing stability and robustness against the ubiquitous noise in the neural system (Mathis & Mozer, 1995). In addition, some parts of the neural system contribute very little to conscious experience (the cerebellum for example (Lemon & Edgley, 2010)), also suggesting that conscious contents do not have one-to-one mapping to the entire state of the neural system. On the other hand, human conscious experience is more detailed than just a simple (e.g. binary) process can represent, suggesting that the state space of conscious experience is much larger than what a single overly coarse-grained binary variable can represent. These facts suggest that conscious processes occur at a particular scale. We currently have only few theories (e.g., Integrated Information Theory (Hoel *et al.*, 2016) and Geometric Theory of Consciousness (Fekete & Edelman, 2011, 2012)) to identify the scale which conscious processes correspond to (also see discussion in Fekete *et al.* (2016)). We refer to this notion as **the scale problem of consciousness** (Fig. 1).

In this article, we propose a new information-based theory of consciousness, called Information Closure Theory of Consciousness (ICT). We argue that every process with a positive non-trivial information closure (NTIC) has consciousness. This means that the state of such a process corresponds one-to-one to conscious content.[1]. We further postulate that the *level* of consciousness corresponds to the degree of NTIC. (for a discussion of the distinction between level versus content of consciousness see Laureys (2005); Overgaard & Overgaard (2010)).

In the following, we first introduce non-trivial informational closure and argue for its importance to information processing for human scale agents (Sec.2). We next argue that through coarse-graining the neural system can form a high degree of NTIC at a specific coarse-grained scale (Sec.3). In the Sec.4, we propose a new theory of consciousness (ICT). We also illustrate how ICT can parsimoniously explain empirical findings from previous consciousness studies (Sec.5) and reconcile several current major theories of consciousness (Sec.6). Finally, we discuss the current theoretical and empirical limitations of ICT and propose the implications from ICT to the current consciousness science (Sec.7).

[1]In the following IC stands for "informational closure" or "informationally closed" and NTIC stands for "non-trivial informational closure" or "non-trivially informationally closed".

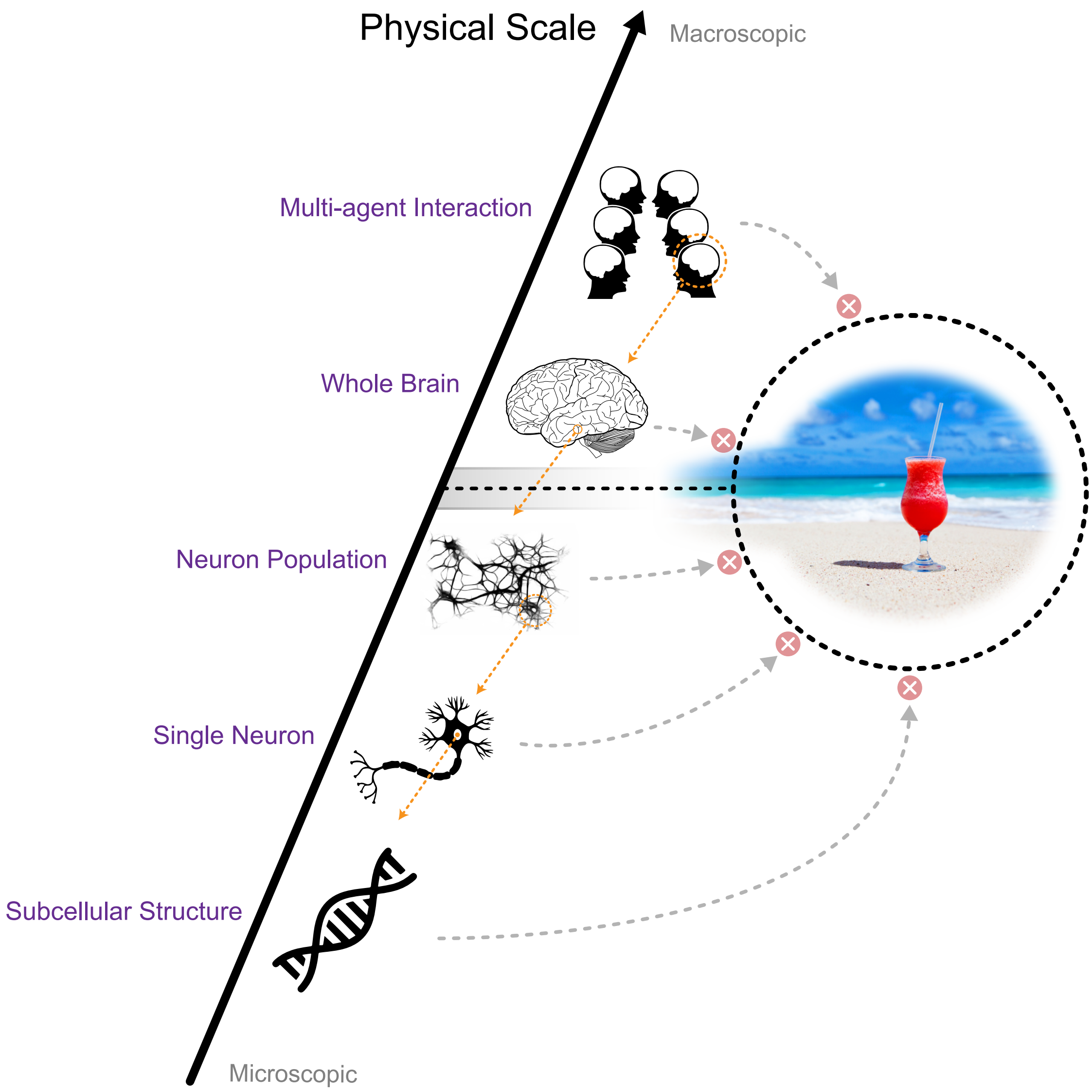

Figure 1: The scale problem of consciousness: Human conscious experience does not reflect information from every scale. Only information at a certain coarse-grained scale in the neural system is reflected in consciousness.

2 Non-trivial Informational Closure

The notion of non-trivial informational closure (NTIC) is introduced by Bertschinger *et al.* (2006). The concept of closure is closely related to system identification in systems theory. One can distinguish a system from its environment by computing the closedness of the system (Luhmann, 1995; Maturana & Varela, 1991; Pattee, 2012; Rosen, 1991). The closedness can be further quantified by information theory.

Consider two processes, the environment process $(E_t)_{t\in\mathbb{N}}$ and the system's process $(Y_t)_{t\in\mathbb{N}}$ and let their interaction be described by the Bayesian network in Fig. 2. Then, information flow J_t from the environment E to a system S at time t can be defined as the conditional mutual information I between the current environment state E_t and the future system state Y_{t+1} given the current system state Y_t

$$\begin{aligned} J_t(E \to Y) \quad &:= I(Y_{t+1}; E_t | Y_t) \\ &= I(Y_{t+1}; E_t) - (I(Y_{t+1}; Y_t) - I(Y_{t+1}; Y_t | E_t)) \end{aligned} \tag{1}$$

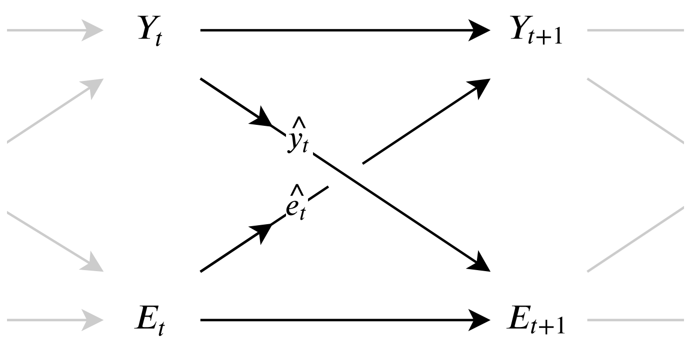

Figure 2: The dependencies between a system Y and its environment E through the channels $\hat{y}_t$ and $\hat{e}_t$.

Bertschinger *et al.* (2006) defines that a system is informationally closed when information flow from the environment to the system is zero.

$$J_t(E \to Y) = 0 \tag{2}$$

Information closure (minimising J_t) is trivial if the environment and the system are entirely independent of each other.

$$I(Y_{t+1}; E_t) = 0 \quad \Rightarrow \quad J_t(E \to Y) = 0 \tag{3}$$

However, informational closure can be formed non-trivially. In the non-trivial case, even though a system contains (or encodes) information about the environmental dynamics, the system can still be informationally closed. In such cases, the mutual information between the current states of the environment and the future state of the system is larger than zero.

$$I(Y_{t+1}; E_t) > 0 \tag{4}$$

This also implies

$$I(Y_{t+1}; Y_t) - I(Y_{t+1}; Y_t | E_t) > 0 \tag{5}$$

And, non-trivial informational closure can be defined as

$$\begin{aligned} NTIC_t(E \to Y) :&= I(Y_{t+1}; Y_t) - I(Y_{t+1}; Y_t | E_t) \qquad (6)\\ &= I(Y_{t+1}; E_t) - I(Y_{t+1}; E_t | Y_t) \qquad (7) \end{aligned}$$

Hence, maximising $NTIC_t(E \to Y)$ amounts to

$$\begin{array}{lll} \text{maximising} & I(Y_{t+1}; Y_t) & \text{and} \\ \text{minimising} & I(Y_{t+1}; Y_t | E_t) & \end{array} \tag{8}$$

One can also maximise $NTIC_t(E \to Y)$ by

$$\begin{array}{lll} \text{maximising} & I(Y_{t+1}; E_t) & \text{and} \\ \text{minimising} & I(Y_{t+1}; E_t | Y_t) & \end{array} \tag{9}$$

This implies the system contains in itself all the information about its own future and the self-predictive information contains the information about the environment. Therefore, to form NTIC, the system can internalise and synchronise with the dynamics of the environment, e.g., model the environment. Furthermore, having high degrees of NTIC entails having high predictive power about the environment. This gives biological agents a great functional and evolutionary advantage.

3 Coarse-graining in the Neural System

The formation of NTIC with a highly stochastic process is challenging. NTIC requires the predictability of the system state and is therefore impeded by noise in the system. Information processing at the microscopic scales (the cellular scale) in neural systems suffers from multiple environmental noise sources such as sensor, cellular, electrical, and synaptic noises. For example, neurons exhibit large trial-to-trial variability at the cellular scale, and are subject to thermal fluctuations and other physical noises (Faisal *et al.*, 2008).

However, it is possible that neural systems form NTIC at certain macroscopic scales through coarse-graining of microscopic neural states. Coarse-graining refers to many-to-one or one-to-one maps which aggregate microscopic states to a macroscopic state. In other words, a number of different micro-states correspond to the same value of the macro-variable (Price & Corry, 2007). Coarse-grainings, can therefore form more stable and deterministic state transitions and more often form NTIC processes. For neural systems this means that a microscopically noisy neural system may still give rise to an NTIC process on a more macroscopic scale.

Indeed, empirical evidence suggests that coarse-graining is a common coding strategy to establish robustness against noise at microscopic scales of the neural system. For instance, the inter-spike intervals of an individual neuron are stochastic. This implies that the state of an individual neuron does not represent stable information. However, the firing rate, i.e. the average spike counts over a given time interval, is more stable and robust against noise such as the variability in inter-spike intervals. Using this temporal coarse-graining strategy, known as rate coding (Adrian, 1926; Gerstner & Kistler, 2002; Maass & Bishop, 2001; Panzeri *et al.*, 2015; Stein *et al.*, 2005), neurons can encode stimulus intensity by increasing or decreasing the firing rate (Kandel *et al.*, 2000). (Stein *et al.*, 2005). The robustness of the rate coding is a direct consequence of the many to one mapping (i.e., coarse-graining).

Population coding is another example of encoding information through coarse-graining in neural systems. In this coding scheme, information is encoded by activation patterns of a set of neurons (a neuron population). In the population coding scheme, many states for a neuron population map to the same state of macroscopic variables which encode particular informational contents, thereby reducing the influence of noise in individual neurons. That is, stable representations can be formed through coarse-graining the high dimensional state space of a neuron population to a lower dimensional macroscopic state space (Binder *et al.*, 2009; Kristan Jr & Shaw, 1997; Pouget *et al.*, 2000; Quian Quiroga & Panzeri, 2009). Therefore, individual neuron states (the microscopic scale) are not informative enough about the complete encoded contents at the population scale (the macroscopic scale). Instead, coarse-grained variables are better substrates for stably encoding information and allow the neural system to ignore noisy interactions at the fine-grained scale (Woodward, 2007).

These two examples show that the known coding schemes can be viewed as coarse-graining, and provide stochastic neural systems with the ability to form more stable and deterministic macroscopic processes for encoding and processing information reliably. We argue that through coarse-graining the neural systems is able to form NTIC processes at macroscopic scales. Based on the merit of coarse-graining in neural systems, we propose a new theory of consciousness in the next section.

4 Information Closure Theory of Consciousness (ICT)

In this section, we propose a new theoretical framework of consciousness: Information Closure Theory of Consciousness (ICT). The main hypothesis is that conscious processes are captured by what we call *C-processes*. We first define C-processes, then state our hypothesis and discuss its implications.

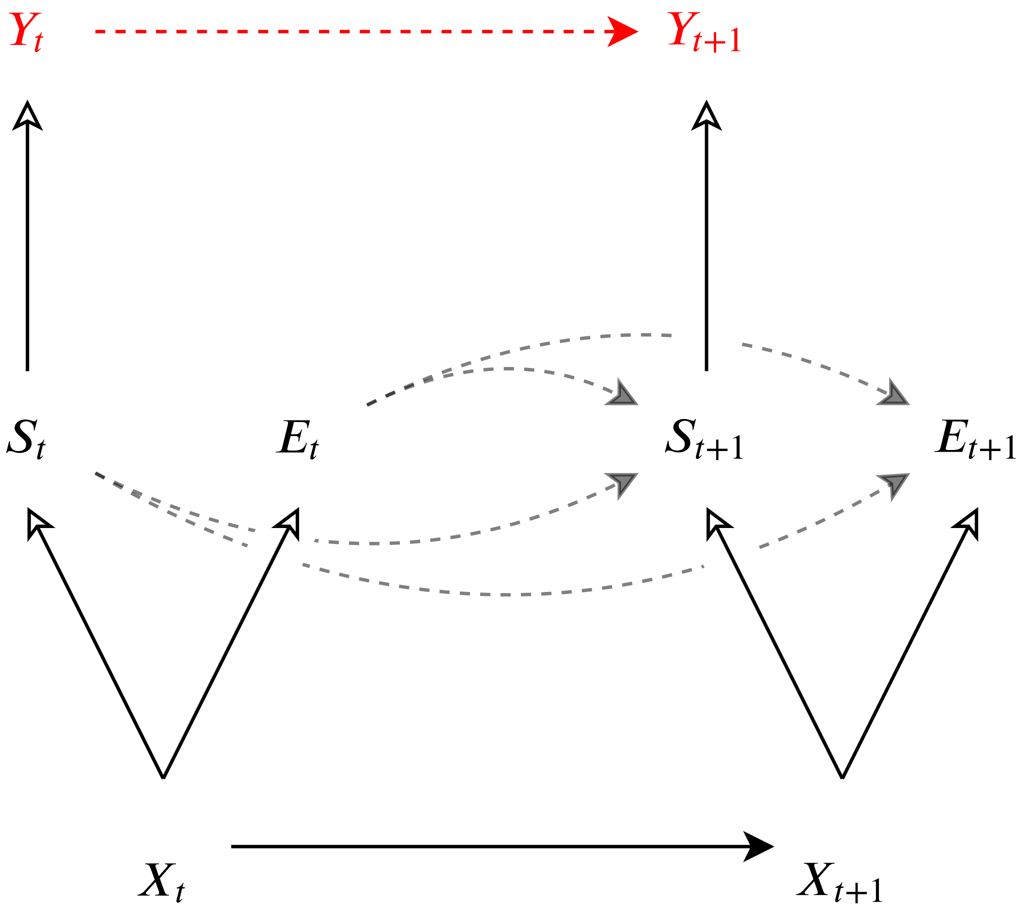

Figure 3: The information flow amounts the universe X, the system S, the environment of the system E, and the coarse-grained process Y of the system S. The solid line with a filled arrow from X_t to X_{t+1} represents the microscopic dynamic of the universe. The solid lines with a empty arrow represent directions of coarse-graining. The dashed lines represents virtual dependencies between two macroscopic variables. The red Y_t, Y_{t+1}, and the red dashed line in between represents a macroscopic process which forms informational closure at a certain coarse-grained scale.

In order to define C-processes we need to define coarse-grainings first. Every coarse-graining is characterised by a function that maps the microscopic process to the coarse-grained macroscopic process. More formally:

Definition 1. *Given a stochastic process X with state space $\mathcal{X}$, a* coarse-graining of X *is a stochastic process Y with state space $\mathcal{Y}$ such that there exists a function* [2] $f_Y : \mathcal{X} \to \mathcal{Y}$ *with* $Y_t = f_Y(X_t)$.

A more general definition of coarse-grainings that maps temporally extended sequences of the microscopic process to macroscopic states are possible but for this first exposure of our theory the simpler definition above is sufficient.

Definition 2. *Given a stochastic process X called the universe process, a* C-process *is a coarse-graining Y of X such that the following two conditions are satisfied (see Fig. 3):*

1. *Y is informationally closed to X*
2. *there exists a pair (S, E) of coarse-grainings of X such that*
    - *Y is a coarse-graining of S,*

[2] Functions in the mathematical sense used here are always either one-to-one or many-to-one.

- *the state space $\mathcal{X}$ of X is equal to the Cartesian product of the state spaces $\mathcal{S}$ and $\mathcal{E}$ of processes S and E respectively, formally $\mathcal{X} = \mathcal{S} \times \mathcal{E}$, and*
- *Y is NTIC to E, formally:*

$$NTIC_t(E \to Y) > 0 \tag{10}$$

Note that, here we applied the same definitions of information flow (Eq. 1)

$$J_t(E \to Y) = I(Y_{t+1}; E_t|Y_t) \tag{11}$$

to the system-environment dependency and the micro-macro scale dependency

$$J_t(X \to Y) = I(Y_{t+1}; X_t|Y_t) \tag{12}$$

even though the Bayesian graphs are different in the two scenarios. Both of these settings have already been used in the literature (see Bertschinger *et al.*, 2006; Pfante *et al.*, 2014b)).

With the two definitions we can state the main hypothesis of ICT

Hypothesis. *A process Y is conscious if and only if it is a C-process of some process X. Also the content of consciousness $C_t^{Content}$ at time t is the state y_t of the C-process at time t and the level of consciousness C_t^{Level} is the degree of NTIC of the process to the environment i.e. $NTIC_t(E \to Y)$:*

$$C_t^{Content} = y_t \tag{13}$$
$$C_t^{Level} = NTIC_t(E \to Y) \tag{14}$$

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$$C_t^{Content} = y_t \tag{15}$$
$$C_t^{Level} = NTIC_t(E \to Y) \tag{16}$$

A concrete example in the context of neuroscience is that X represents the microscopic scale of the universe, S a cellular scale process in the neural system, Y a more macroscopic process of the neural system coarse-grained from the cellular scale process S, and E the environment which the cellular level process S interacts with. The environment E may include other processes in the neural system, the sensors for perception and interoception, and external physical worlds.

Based on the hypothesis, ICT leads to five core implications:

Implication 1. Consciousness is information. Here, "informative" refers to the resolution of uncertainty. Being in a certain conscious state rules out other possible conscious states. Therefore, every conscious percept resolves some amount of uncertainty and provides information. This implication is also in agreement with the "axiom" of *information* in Integrated Information Theory (IIT 3.0) which claims that "…an experience of pure darkness is what it is by differing, in its particular way, from an immense number of other possible experiences…" (Oizumi *et al.*, 2014, P. 2)

Implication 2. Consciousness is associated with physical substrates and the self-information of the conscious percept is equal to the self-information of the corresponding physical event. This is a direct implication from our hypothesis that every conscious percept $C_t^{Content}$ corresponds to a physical event y_t.

Implication 3. Conscious processes are self-determining. This is a direct implication of the requirement that Y is informationally closed with respect to X. To be informationally closed with respect to X, no coarse-graining knows anything about the conscious process' future that the conscious process does not know itself. This self-determining characteristics is also in line with our daily life conscious experience which often shows stability and continuity and is ignorant of the stochasticity (e.g., noise) of the cellular scales.

Implication 4. Conscious processes encode the environmental influence on itself. This is due to the non-triviality of the informational closure of Y to E. At the same time all of this information is known to the conscious processes themselves since they are informationally closed with respect to their environments. This also suggests that conscious processes can model the environmental influence without knowing more information from the environment.

Implication 5. Conscious processes can encode environmental information (by forming NTIC), however, be ignorant to part of the information of more microscopic processes (from Implication 3 and 4). This is in line with our conscious experience that information that every conscious percept provides represent rich and structured environmental states without involving all the information about microscopic activities.

4.1 Level of Consciousness is Equal to the Degree of NTIC of a Process

According to Eq. 8, ICT implies that conscious levels are determined by two quantities.

First, to form a high level of NTIC, one can increase the mutual information $I(Y_{t+1}; Y_t)$ between the current internal state Y_t and the future internal state Y_{t+1}. In other words, conscious levels are associated with the degree of self-predictive information (Bialek *et al.*, 2001). This mutual information term can be further decomposed to two information entropy quantities:

$$I(Y_{t+1}; Y_t) = H(Y_{t+1}) - H(Y_{t+1}|Y_t) \tag{17}$$

This implies that a highly NTIC process must have rich dynamics with self-predictability over time. Another implication is that complex systems can potentially attain higher levels of consciousness due to the larger information capacities needed to attain high mutual information. This outcome is consistent with the common intuition that conscious levels are often associated with the degree of complexity of a system.

Second, one can minimise the conditional mutual information $I(Y_{t+1}; Y_t|E_t)$ to increase the level of NTIC. This quantity suggests that conscious level increases with the amount of information about the environment state E_t that the NTIC process encodes in its own state Y_t. In other words, Y_t should not contain more information about Y_{t+1} than E_t. An important implication is that agents interacting with a complex environment have the chance to build a higher level of NTIC within their systems than those living in a simple environment. In other words, the level of consciousness is associated with environmental complexity.

It is important to note that NTIC can be a non-monotonic function of the scale of coarse-graining At the finest scale we consider the whole universe X as the process Y. then, since Y is a coarse graining of S we have $Y = S = X$. In this case the environment E corresponding to the universe seen as a system is the constant coarse-graining[3] and therefore the mutual information $I(E_t; Y_{t+1}) = 0$ and the transfer entropy $I(Y_{t+1}; E_t|Y_t)$ are zero. Then NTIC of the universe with respect to its environment is zero and X can never be a C-process.

If we now increase the scale of Y, this allows S to also reduce in scale and therefore E can become more and more fine-grained. This means that the mutual information $I(E_t; Y_{t+1})$ between E and Y can at least potentially become positive. Up to the point where E accounts for half of the bits of X and S for the other half (and we have $Y = S$) the maximally possible mutual information $I(E_t; Y_{t+1})$ increases. Even further refining E then again leads to a reduction of the maximally possible $I(E_t; Y_{t+1})$.

On the other extreme, when $E = X$ the system state space must be the singleton set and NTIC from E to Y must again be zero. Therefore, processes at certain scales of coarse-graining in the neural system can form high degrees of NTIC (Fig. 4). ICT indicates that human consciousness occurs at the scale of coarse-graining where higher NTIC is formed within the neural system.

[3] Recall that, for a system with state space $\mathcal{S}$ the environment state space $\mathcal{E}$ must be such that $\mathcal{X} = \mathcal{S} \times \mathcal{E}$. I $\mathcal{S} = \mathcal{X}$ then we need $\mathcal{E}$ with $\mathcal{X} \times \mathcal{E} = \mathcal{X}$ such that $\mathcal{E}$ must be a singleton set. All coarse-grainings mapping $\mathcal{X}$ to a singleton set are constant over $\mathcal{X}$.

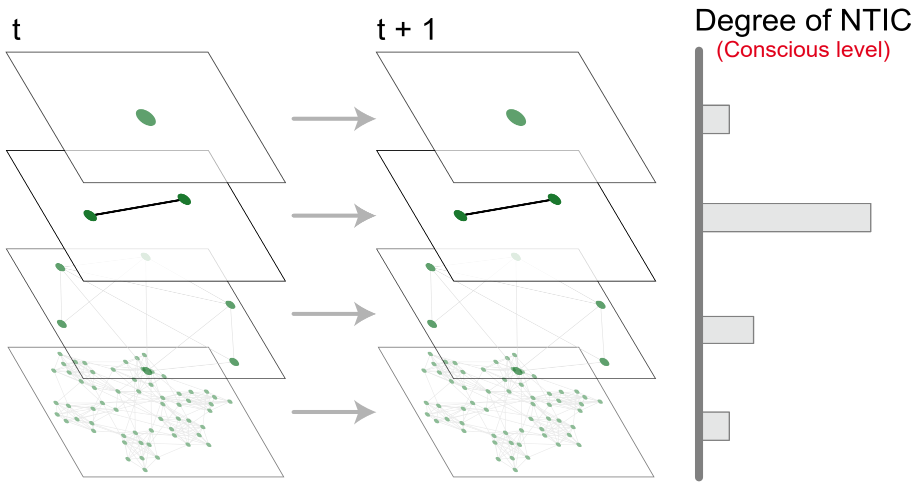

Figure 4: A non-monotonic relationship between scale of coarse-graining and level of consciousness.

4.2 Conscious Contents Corresponding to States of a NTIC Process

ICT proposes that conscious contents correspond to the states of NTIC processes (Eq. 15). This implies that the size of the state space of an NTIC process is associated with the richness of conscious contents that the process can potentially have. Therefore, a complex NTIC process with a high dimensional state space can have richer conscious experience than a simple NTIC process can have. This outcome is consistent with the intuition that the richness of conscious contents is associated with the complexity of a system.

As mentioned above, informational closure can happen between scales of coarse-graining within a single system. Thus, a macroscopic NTIC process can be ignorant to its microscopic states. ICT argues that human conscious contents do not reflect cellular scale activity because the conscious process which corresponds to a macroscopic NTIC process is informationally closed to the cellular scale in the human neural system. Further more, since NTIC processes are informationally closed, each of them can be considered as a reality. In the extreme case, when the information flow from its microscopic processes and environment to the informationally closed process is completely zero (Eq. 2), the future states of the process is only determined by its past states.

Importantly, NTIC processes internalise the environmental dynamics in its states (also see P. 4 Bertschinger *et al.*, 2006). This suggests that a NTIC process can be considered as a process that models the environmental dynamics.This implication fits well with some theories of consciousness (for example, world simulation metaphor (Revonsuo, 2006)). Note that ICT doesn't assume that generative models are necessary for consciousness. The implication is a natural result of processes with NTIC.

Finally, a coarse-graining can be a many to one map from microscopic to macroscopic states and ICT proposes that conscious contents $C^{Content}$ is the state of the NTIC process Y. Therefore, ICT implies multiple realisation thesis of consciousness (Bechtel & Mundale, 1999; Putnam, 1967) which suggests that different physical implementations could map to the same conscious experience.

4.3 Reconciling the Levels and Contents of Consciousness

While it is useful to distinguish the notion of the levels and contents of consciousness, whether they can be clearly dissociated has been a matter of debate (Bayne *et al.*, 2016; Fazekas & Overgaard, 2016). In ICT, conscious levels and conscious contents are just two different properties of NTIC processes, and, therefore, naturally reconciles the two aspects of consciousness. In an NTIC process with a large state space, conscious contents should also consist of rich and high dimensional information. Therefore, this framework integrates the levels and the contents of consciousness in a coherent fashion by providing explicit formal definitions of the two notions.

According to Sec. 4.1 and Sec. 4.2, an important implication from ICT is that both conscious levels and conscious contents are associated with the state space of an NTIC process Y. A large state space of Y contributes conscious levels through the mutual information $I(Y_{t+1}; Y_t)$ and also contributes richer conscious contents by providing more possible states of conscious processes. ICT therefore explains why, in normal physiological states, conscious levels and conscious contents are often positively correlated (Laureys, 2005). This implication is also in line with the intuition in which consciousness is often associated with complex systems.

5 Conscious Versus Unconscious Processing

In this section, we show how ICT can explain and make predictions about what processes are more conscious than others. ICT is constructed using information theory. Therefore, ICT can provide predictions based on the mathematical definitions.

5.1 Unconscious Processing

Regarding unconscious processing, we highlight two scenarios which decrease the degree of NTIC of a process, thereby making the process less conscious.

Processes that are not Informationally Closed

The first scenario is that of a system partially observing the environment in such a way that the current observation is insufficient to predict the next. In this situation we can show that a system passively processing the observations (including copying them) achieves lower values of NTIC and therefore lower levels of consciousness than a system that is able to accurately predict the observations. ICT leads to some surprisingly simple conscious processes. Consider the case already noted by Bertschinger *et al.* (2006) where the environment process is deterministic (or close to it) and the system just copies the environment process. Then the system can achieve positive values of NTIC with respect to the environment. ICT states that such processes are conscious.

However, in more realistic cases the system cannot copy the entire environment state because it observes only part of it.

We show in Appendix 9 that whenever the environment has itself more predictable dynamics than the observations there is potential for a predictive process to achieve higher NTIC than a copying system or any system that only processes its last observations without taking into account other internal memory. Similar to Bertschinger *et al.* (2006) we will refer to systems of the latter type as *passive*. We will call all other systems that achieve positive NTIC *predictive*. Note that the predictive process might need to be more complex than the system that only copies its observations.

We tentatively assume below that for a feed-forward network which can be seen as implementing a function from an extended history of past observations to the system state there also always exist systems that achieve higher NTIC. This remains to be verified.

Let us now look at some examples of this scenario.

The first are reflexive behaviours (Casali *et al.*, 2013). In ICT, if we can view reflexive behaviours as situations in which the internal state Y_t, which triggers reflexive action, is determined by the environment state E_{t-1} overruling the influences from its own past Y_{t-1}. Such interpretation of reflexive behaviour from the viewpoint of ICT naturally explains why we are less conscious of external stimuli causing reflexes than of others.

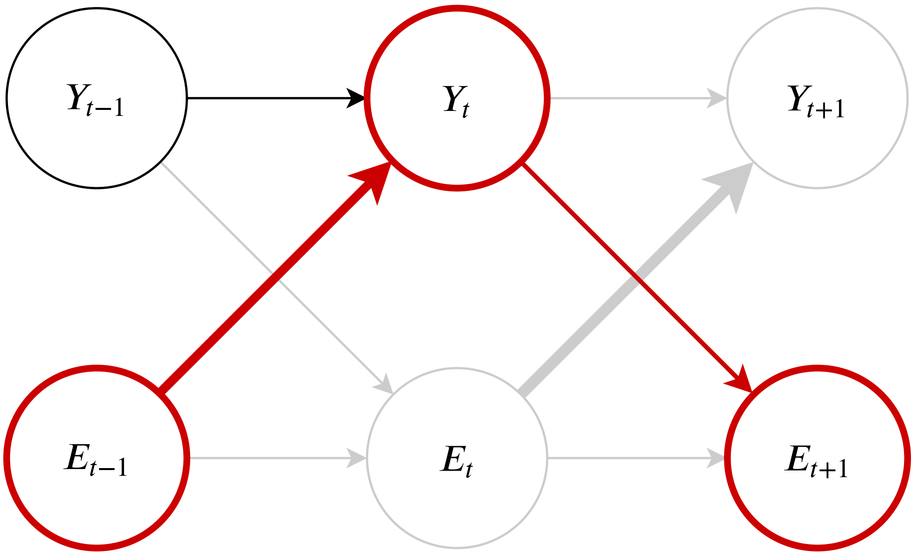

Figure 5: A diagram depicting the information flow in reflexive behaviours (shown by the red nodes and arrows) happening through the interaction between a process Y and its environment E. In such situations, the internal state Y_t is mostly dependent on the environment state E_{t-1} but less on its past state Y_{t-1}. Therefore, the process Y is not informational closed. As a consequence, Y is unable to form high NTIC and, therefore, remain less conscious or unconscious.

The same principle can be applied to interpret blindsight (Humphrey, 1970, 1999, 1974) and procedural memory (Ashby *et al.*, 2010; Doyon *et al.*, 2009) which are often considered as unconscious processes. Blindsight patients are able to track objects, avoid obstacles, and make above chance-level visual judgements with degraded or missing visual experience. However, in some cases, they may still preserve some forms of conscious experience (see Mazzi *et al.* (2016); Overgaard (2011)). We argue that action outputs of blindsight can be directly guided by sensory inputs through stimulus-response maps. The corresponding neural circuits are passive and therefore do not achieve the same level of informational closure as processes/behaviours involving prediction. According to ICT we are therefore less conscious of them.

Similarly, for procedural memory, the transitions of the part of the neural system determining the action sequences largely depend on the environmental states. Procedural memory may therefore be considered a passive process. ICT then predicts that we are less conscious of procedural memory than of more predictive processes.

ICT also offers an interpretation as to why patients with visual apperceptive agnosia (James *et al.*, 2003) can perform online motor controls without visual awareness of action targets (Whitwell *et al.*, 2014).

Networks with recurrent loops employ information stored in their own past states that is not necessarily a function of a single time-step observation. If it indeed turns out to be true that for every pure feed-forward network there are non-feed-forward systems achieving higher NTIC then ICT predicts that the latter systems achieve higher levels of consciousness.

This would coincides with theories of consciousness emphasising the importance of recurrent circuits to consciousness (Edelman, 1992; Lamme, 2006; Tononi & Koch, 2008).

Processes are Trivial closed

According to ICT, when encoded information in a process is trivial, i.e. no mutual information between the process states and its environment states $I(Y_{t+1}; E_t)$ (Eq. 9), this could lead low NTIC. In such case, this process is considered to be unconscious due to the low level of NTIC. This implies an isolated process which is simply informationally closed is insufficient to be conscious. This mathematical property of ICT provides a natural and intuitive (but only partial, see the current challenge in Sec. 7) solution to the boundary and the individuality problem of consciousness [4] (Raymont & Brook, 2006). Consider a NTIC process Y and an isolated informationally closed

[4] The boundary problem of consciousness refers to identifying physical boundaries of conscious processes and the individuality problem of consciousness refers to identifying individual consciousnesses in the universe.

process $\hat{Y}$ with only trivial information. Adding $\hat{Y}$ to Y can still keep informational closure, but, however, does not increase non-trivial information, i.e. doesn't affect consciousness.

$$\begin{aligned}
I(Y,\hat{Y};E) &= H(Y,\hat{Y}) - H(Y,\hat{Y}|E) \\
&= H(Y) + H(\hat{Y}|Y) - (H(Y|E) + H(\hat{Y}|Y,E)) \\
&= H(Y) + H(\hat{Y}) - (H(Y|E) + H(\hat{Y})) \\
&= H(Y) - H(Y|E) \\
&= I(Y;E)
\end{aligned} \tag{18}$$

This implies that isolated processes with trivial information do not contribute consciousness and should be considered being outside the information boundary of the conscious processing (for more details of the boundary detection procedure, see Krakauer *et al.* (2014)). This property also implies that consciousnesses do not emerge from just aggregating informationally closed (isolated) processes which contain trivial information.

5.2 Conscious Processing

According to ICT, we claim that any process, system, or cognitive function which involves any NTIC process should be accompanied by conscious experience.

Previous consciousness research has identified a number of diverse cognitive processes often accompanied by conscious experience. ICT provides an integrated account for the reason why these processes involve conscious experience. As mentioned above, an NTIC process can be seen as an internal simulation engine for the agent-environmental interactions (Bertschinger *et al.*, 2006). Therefore, information encoded in NTIC processes is essential for several cognitive processes.

One of the most valuable information is the predictions about the environmental states. Cognitive functions requiring agent-scale environmental predictions are likely to recruit NTIC processes and therefore accompanied by conscious experience, for example planning and achieving long term goals.

Second, as a simulation engine, with a given initial state, an NTIC process can self-evolve and simulate the environmental transitions. Cognitive functions involving simulations are expected to involve NTIC processes. Consequently, mental simulation, imagination, computing alternative realities, and generating counterfactuals often come with conscious experience.

Third, as an informationally closed system, an NTIC process can still provide environmental information without new sensory inputs. This is crucial for many types of off-line processing. Therefore, in contrast to reflexive-like behaviours mentioned above (Sec. 5.1), behaviours requiring off-line computations (Himmelbach & Karnath, 2005; Milner *et al.*, 1999; Revol *et al.*, 2003) often involve conscious experience.

Finally, for agents adapting to complex environments (e.g., human being), any state of the NTIC process can be seen as an integration of high dimensional information. To accurately encode information about the complex environmental states and transitions, the NTIC process requires knowledge about the complex causal dependencies involved in the environment. Therefore, cognitive functions requiring large scale integration are likely to involve NTIC processes and accompanied by conscious experience.

Note that many of the claims above are compatible with several theories of consciousness which highlight the connection between consciousness and internal simulation, predictive mechanism, or generative models inside a system (e.g. world simulation metaphor (Revonsuo, 2006), predictive processing and Bayesian brain (Clark, 2013; Hohwy, 2013; Seth, 2014), generative model and information generation (Kanai *et al.*, 2019)). Instead of relating functional or mechanistic aspects of a system to consciousness, ICT captures common informational properties underlying those cognitive functions associated with consciousness. As such, ICT does not assume any functionalist perspective of consciousness, which associate specific functions to consciousness. That is to say, since ICT associates information with consciousness, functional features accompanied by consciousness are collateral consequences of neural systems utilising NTIC processes for adaptive functions.

In sum, we argue that cognitive functions involving the NTIC process are inevitably accompanied by consciousness. Having an NTIC process is potentially an effective approach to increase fitness in the evolution. It is likely that biological creatures evolve NTIC processes at some point in the evolution. Due to the fundamental relation between information and consciousness, biological creatures also evolve different degrees of consciousness depending on the physical scales and the complexity of the environments they adapt to.

ICT starts with a non-functional hypothesis, however, it accounts for the association between functional and consciousness. ICT further demonstrates remarkable explanatory power for various findings of conscious and unconscious processing.

6 Comparison with Other Relevant Theories of Consciousness

In this section, we compare ICT with other relevant theories of consciousness.

6.1 Multilevel Views on Consciousness and Cognition

ICT proposes that conscious processes can occur at any scale of coarse-graining which forms NTIC within a system. This suggests that the scale of coarse-graining is critical for searching and identifying the information corresponding to consciousness. A few versions of multilevel views on consciousness have previously been (explicitly or implicitly) proposed. To our knowledge, Pennartz's neurorepresentational theory (also called Neurorepresentationalism, (Pennartz, 2015, 2018)) is the proposal closest to the multilevel view of ICT. Similar to Neurorepresentationalism, the concept of levels in ICT is also relevant to Marr's level of analysis (Marr, 1982; Pennartz, 2015, 2018). However, ICT suggests that coarse-graining is necessary only when the microscopic processes are stochastic (e.g. the neural system). An NTIC process can be formed in a noise-free deterministic system without coarse-graining. According to ICT, this NTIC process is sufficient to be conscious. Another fundamental difference between ICT and Neurorepresentationalism is that Neurorepresentationalism takes functionalist perspective and suggests consciousness should serve high-level world-modelling and makes a best guess about the interaction between the body and the environment. However, ICT is grounded by non-functional informational hypothesis. Therefore, ICT provides a more fundamental explanation for the scale problem of consciousness.

Another well-known proposal based on multilevel views is the Intermediate Level Theory of Consciousness (Jackendoff, 1987; Prinz, 2007, ILT). ILT proposes that conscious experience is only associated with neural representations at intermediate **levels of the sensory processing hierarchy** (e.g., the 2.5D representation of visual processing) rather than lower (e.g., pixel) or higher (e.g., abstract) levels of the sensory hierarchy.

Here, we want to make clear that the "level" in ICT refers to the **scales of coarse-graining** instead of the "level" for the cortical anatomy or sensory processing. It is important to note that the coarse-graining direction is an orthogonal dimension irrespective of the level of anatomy or the level of information processing hierarchy in the neural system (see Fig. 6). Because ILT focuses on the levels of the sensory processing hierarchy and ICT focus on informational closure among the levels of coarse-graining, the two theories are fundamentally different.

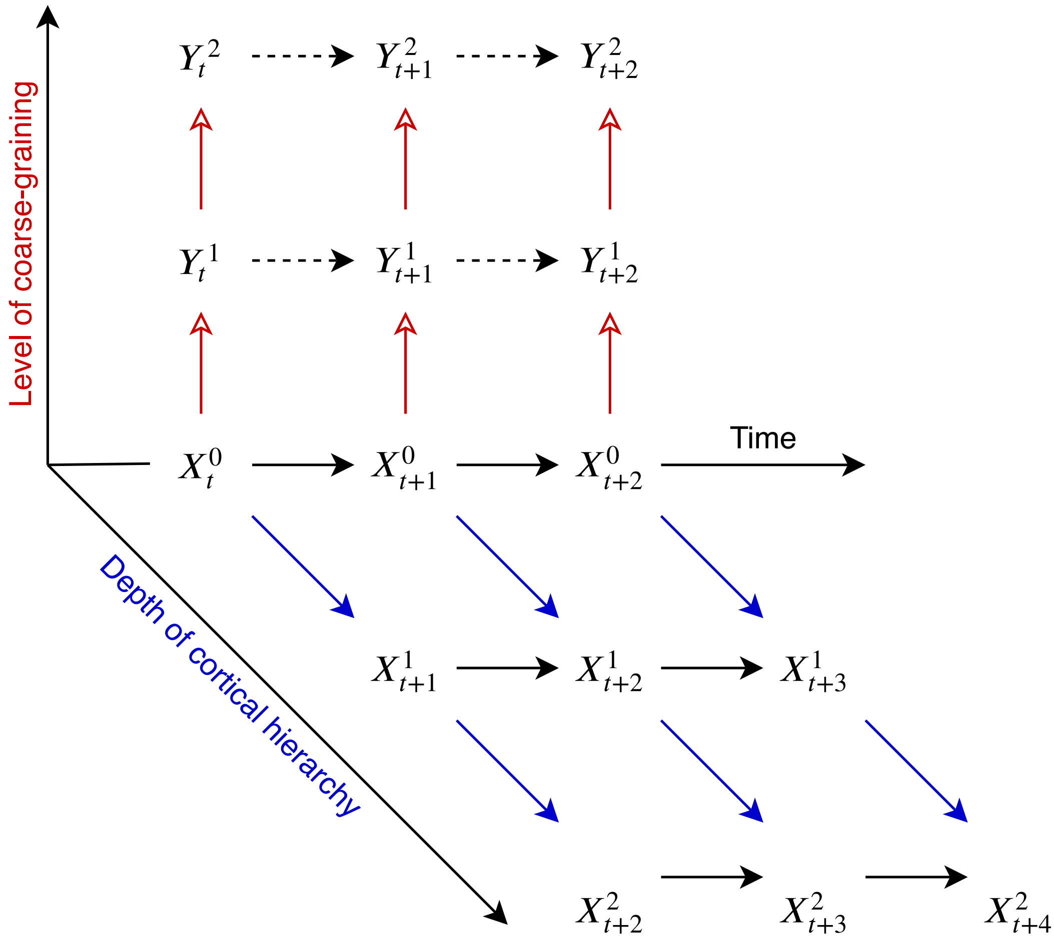

Figure 6: The distinction between the level of coarse-graining and the level of the cortical hierarchy. X and Y represent the microscopic and macroscopic coarse-grained variables, respectively. X^0 represents the microscopic states at the upstream of the cortical hierarchy. The red empty arrows represents the directions of coarse-graining and the blue arrows represent the directions of the physical dependencies in the cortical hierarchy from the upstream to the downstream. (Some variables and dependencies are omitted for clarity.)

6.2 Integrated Information Theory

Integrated information theory (IIT) states that consciousness is integrated information and system's consciousness is determined by its causal properties (Tononi *et al.*, 2016). ICT is in line with IIT in that informational properties are thought to underlie consciousness. In this section, we will discuss ICT in the light of IIT.

The concept of "information": In IIT, information refers to "integrated information": "Information that is specified by a system that is irreducible to that specified by its parts." (Tononi *et al.* 2016) In ICT, information refers to "self-information", i.e. information about the states of conscious experience and the physical states of a process. Therefore, IIT focuses more on the relationships between consciousness and causal interactions among elements within a system, whereas ICT focuses more on the informational relationships between conscious experience and being in a certain state of a process.

The "Exclusion" axiom in IIT: In IIT, the Exclusion axiom claims that of all overlapping sets of elements, only one set with maximal integrated information can be conscious. The exclusion axiom should be applied over elements, space, time, and scales (Hoel *et al.*, 2016; Oizumi *et al.*, 2014). Different from IIT, ICT allows multiple consciousnesses coexist across different scales of coarse-graining within a system if they are informationally closed from each other. The two distinctive predictions decisively pinpoint the core concepts of the two theories.

The concept of "integration": In IIT, integrated information is one of the core concept of defining conscious individuals. In the current paper, we did not include the notion of integrated information within ICT. This, however, results in one of the current weaknesses of ICT that it lacks the ability to individuate NTIC processes in some extreme cases (i.e., the problem of individuality). We discussed this weaknesses in Sec. 7.

Prediction after system damaged: ICT and IIT lead to different predictions when a system suffers from a damage. For example, considering a densely connected networks whose dynamics forms an NTIC process. If we cut the network in half, IIT would predict that this results in two consciousnesses because elements in both networks still maintain high degrees of interactions. In contrast, ICT would predict that this operation could completely destroy NTIC rendering both parts unconscious.

6.3 Predictive Processing

Predictive processing (PP) is a powerful framework which integrates several ideas from neuroscience. This emerging theoretical framework posits that neural systems constantly generate predictions about incoming sensory signals and updates predictions based on prediction errors between predictions and sensory signals. According to PP, neural systems constantly perform unconscious statistical inference about hidden causes in the external environment. The perceptual contents are the "best guess" about the environment states including these hidden causes (Clark, 2013; Hohwy, 2013). PP is well integrated with Bayesian brain hypothesis and has been used to interpret conscious perception in many domains (Hohwy, 2013; Seth, 2014).

PP is a powerful explanatory framework for diverse brain functions. However, to serve as a theory of consciousness, PP is still incomplete due to two explanatory gaps. First, it has been known that the neural system is equipped multiple predictive mechanisms. Apparently, not all the predictive mechanisms are involved in conscious processes (e.g. mismatch negativity, Näätänen *et al.* (2007)). PP needs to explain the difference between conscious and unconscious predictive mechanisms.

Second, PP can be considered as a sophisticated computation for perceptual inference. It takes von Helmholtz's conception of perception as unconscious inference. Thus, only the most probable outcome computed by the inference processes can be conscious while other details of the computation remain unconscious. PP also needs to explain how unconscious inferences is able to give rise to conscious results. In short, while PP is often discussed in the context of consciousness, these explanatory gaps prevent PP from being a theory of consciousness.

ICT is well compatible with PP. Crucially, ICT further provides natural and fundamental explanations to fills the two explanatory gaps which PP encounters. According to the definition of NTIC, a process with high NTIC can be regarded as a powerful predictive machine which has accurate self-predictive information ($I(Y_{t+1}; Y_t)$, E.q. 6) and concurrently incorporates environmental information into its dynamic ($I(Y_{t+1}; Y_t|E_t)$, E.q. 6). This predictive nature of NTIC processes is in agreement with the core notion of PP in which the conscious contents are always the predicted (inferred) outcome of our predictive mechanisms. Second, due to the informational closure to the environment, the encoded information about its environment in an NTIC process can be seemed as "the best guess" about the external environment in the context of Bayesian inference.

So, eventually, why are some predictive information conscious and some are not? ICT predicts that only the predictions generated from mechanisms involving the NTIC process are conscious. Note that predictive processes are not necessary to involve NTIC processes. A predictive process can make prediction about the future state of its environment based on the current sensory inputs. In this case, the the process is not informationally closed and could not be conscious.

According to ICT, we further propose that we can only be aware of the predictions from predictive processes due to informational closure to computational details of microscopic predictive processes. The macroscopic NTIC process only acquires the coarse-grained summary statistics of the microscopic processes. In other words, we predict that the computation of the statistical inferences of PP is implemented at microscopic (cellular) scales in the neural system.

Finally, we consider PP as an potential empirical implementation of NTIC processes. To maintain accurate information about the environment encoded in an NTIC process, one can open an information channel between the process and the environment for minimal information flow to correct the divergence between them. This proposal is compatible with PP which suggests that PP systems updates (corrects) the current estimations by computing prediction errors between predicted and real sensory inputs.

6.4 Sensorimotor Contingency

Sensorimotor contingency (SMC) theory of consciousness proposes that different types of SMCs give rise to different characteristics of conscious experience (O'Regan & Noë, 2001). The theory radically rejects the view that conscious content is associated with internal representations of a system. Rather, the quality of conscious experience depends on agents' mastery of SMCs. SMC emphasises that the interaction between a system and its environment determines conscious experience.

ICT is not compatible with SMC. As mentioned in Sec. 5, a process directly maps the sensory states to the action states is insufficient to be NTIC. Therefore, learning contingencies between sensory inputs and action outputs does not imply NTIC. Hence, ICT predicts that having sensorimotor contingencies is neither a necessary nor a sufficient condition for consciousness. In fact, empirically, with extensive training on a sensorimotor task with a fixed contingency, the task can be gradually performed unconsciously. This indicates that strong SMCs do not contribute conscious contents. In contrast, ICT suggests that, with extensive training, the neural system establishes a neural mapping from sensory inputs to action outputs. This decrease the level of informational closure and, as a result, decrease the conscious level of this process. This outcome strongly supports ICT than SMC.

Nevertheless, ICT does appreciate the notion that interactions between a process and its environment is crucial to shape conscious experience. As mentioned above, to form NTIC, a process needs to encode environmental transitions into its own dynamic. Therefore, information of agent-environment interaction should also be encoded in the NTIC process, and therefore, shape conscious contents in a specific way.

Different from the classical SMC, a new version of SMC, Predictive Processing of SensoriMotor Contingencies (PPSMC), proposed by Seth (2014, 2015) combines SMC and the predictive processing framework together. PPSMC emphasises the important role of generative models in computing counterfactuals, inferring hidden causes of sensory signals, and linking fictive sensory signals to possible actions. According to ICT, if the generative model involving the NTIC process for the computation of counterfactuals, PPSMC will be compatible to our theory and may have strong explanatory power on some specific conscious experience.

6.5 Global Workspace Theory

Global workspace theory (GWT; Baars (1988, 1997, 2002)) or Global Neuronal Workspace theory (GNWT; Dehaene & Changeux (2011); Dehaene & Naccache (2001); Dehaene *et al.* (1998)) states that the neural system consists of several specialised modules and a central global workspace (GW) which integrates and broadcasts information gathered from those specialised modules. Only the information in the global workspace reaches conscious awareness, and information outside of it remains unconscious. These modules compete with each other to gain the access to the GW and the information from the winner triggers an all-or-none "ignition" in the GW. Information in the GW is broadcasted to other modules. Conscious contents then are associates with the information that gains access to the internal global workspace Dehaene *et al.* (2017).

While GWT emphasises the importance of global information sharing as a basis of consciousness, the precise meaning of information broadcasting has been somewhat unclear if one tries to describe it more formally in the language of information theory. ICT offers one possible way to consider the meaning of broadcasting in GWT. Specifically, one could interpret the global workspace as the network of nodes where information is shared at the scale of NTIC where communication is performed through macro-variables that are linked via mutual predictability. That is, global workspace should be also NTIC. While this link remains speculative at this point, this interpretation encourages empirical studies into the relationship between the contents of consciousness and macrostate neural activities that are mutually predictive of each other.

7 Limitation and Future Work

As a brand new theory of consciousness, ICT is still far from completion. In the following, we discuss the current limitations and challenges of ICT and point out the potential future research directions.

It's important to clarify that ICT does not intend to completely solve the hard problems of consciousness (Chalmers, 1995). Knowing the state of a conscious process does not allow us to answer "What is it like to be in this state of this process" (Nagel, 1974). Instead, ICT focuses more on bridging consciousness and the physical world using information theory as a common language in between.

The current version of ICT cannot entirely solve the problem of individuality in some extreme circumstances. In common cases, one can identify individual consciousnesses by computing the levels of NTIC of a process. This approach can also be applied to finding the boundaries of individual consciousnesses (for details of the boundary detection procedure, see Krakauer *et al.* (2014)). However, in some specific circumstances, individuality of consciousness is not clear. For instance, we can define a new process Y and also its environment E by recruiting two independent NTIC processes Y^1 & Y^2 and their environments E^1 & E^2, respectively. So that $Y = \{Y^1, Y^2\}$ and $E = \{E^1, E^2\}$. In such case, the new process Y will also be NTIC to E. Therefore, the current version of ICT cannot determine whether there are two smaller consciousnesses or one bigger consciousness (or 3 coexisting consciousnesses). The problem of individuality is a significant theoretical weakness of the current version of ICT. The notion of integration is a possible remedy for this issue and we will address this issue more explicitly in our future work using the concept of synergy.

The current version of ICT assume that consciousness is only contributed by non-trivial rather than trivial information encoded in a process. In other words, how much information about environmental states and dynamics encoded in a process is a key quantity for consciousness. However, we do not exclude the possibility that environmental information may be just a proxy of other informational quantities. More theoretical work is needed to elucidate the role of environments. This issue will also be discuss in our next theoretical paper.

Explaining conscious experience during dreaming is always a challenge to all the theories of consciousness. ICT currently does not have a certain answer to dreaming. However, we want to emphasise that not all the processes in the neural system are NTIC. This is trivial since some processes are evidently not informationally closed. They mainly passively react to sensory inputs or other processes in the neural system. To the conscious (NTIC) process, the rest of the neural system is part of the environment, and undoubtedly retains some degree of activity during sleep and dreaming. We speculate that, during dreaming, the neural system stably forms an NTIC process with respect to its environment, i.e. the other parts of the neural system. However, at the current stage, this is mere speculation. Searching for the NTIC process(es) during dreaming is a crucial step to extend the scope of ICT in future research.

Empirically, a major challenge to ICT is to find proper coarse-graining functions which map microscopic processes to macroscopic NTIC processes. This will become an imperative issue of finding neurological supporting evidence for ICT. To find proper coarse-graining functions among infinite candidates (Price & Corry, 2007) seem to be very challenging. Nevertheless, there are still theoretical and technical progresses recently that may contribute to solving this issue. For example, the concept of *causal emergence* proposed by Hoel (Hoel, 2018; Hoel *et al.*, 2013) has been further developed recently. Causal emergence is highly relevant to the relationship between informational closure and coarse-graining. In their new study by Klein & Hoel (2019), they started to compare how different coarse-graining functions influence causal emergence at macroscopic scales. Pfante *et al.* (2014a,b) provides thorough mathematical analyses on level identification including informational closure. In neuroscience, the understanding of neural population codes also achieves a tremendous progress due to the advancement of recording technique and data science (Kohn *et al.*, 2016; Panzeri *et al.*, 2015). Gamez (2016) has also systematically described relevant issues in terms of finding data correlates of consciousness amount different levels of abstraction. We believe that interdisciplinary research is required to narrow down the scope of searching the coarse-graining functions and conscious processes at the coarse-grained scales in the neural system and beyond.

In this article, we do not use a state-dependent formulation of NTIC. However, we believe that the state-dependent NTIC is essential to describe the dynamics of conscious experience. Therefore, further research using point-wise informational measures to construct state-dependent NTIC is needed for the next version of ICT.

Finally another empirical challenge to ICT is the of empirical supporting evidence. This is understandable because the concept of NTIC is relatively new in the history of information science, not to mention in neuroscience. Very few experiments and data collections are designed for examining NTIC properties in neural systems. To our knowledge, only two studies (Palmer *et al.*, 2015; Sederberg *et al.*, 2018) coincidentally examine relevant properties in salamander retina. They found that the a large group of neural populations of retinal ganglion cells encoded predictive information about external stimuli also had high self-predictive information about their own future states. This result is in line with the characteristic of NTIC. We expect that there will be more empirical studies examining relevant neural properties of NTIC.

8 Conclusions

In this paper, we introduced **Information Closure Theory of Consciousness (ICT)**, a new informational theory of consciousness. ICT proposes that a process which forms **non-trivial informational closure (NTIC)** is conscious and through coarse-graining the neural system can form NTIC processes, i.e., conscious processes, at a certain macroscopic scales. ICT considers that information is a common language to bridge the gap between conscious experience and the physical reality. Using information theory, ICT proposes computational definitions for both conscious level and conscious content. This makes ICT be able to generalise to any system beyond the human brains.

ICT provides explanation for various findings from research of conscious and unconscious processing. The implications of ICT point out that the scales of coarse-graining play a critical role in searching for neural substrates of consciousness. Improper measurements, e.g., too fine or too coarse in terms of the scale of measurements, of neurophysiological signals may lead to misleading results and misinterpretations.

ICT reconciles several theories of consciousness. ICT indicates that they conditionally coincide with ICT's implications and predictions but, however, not the fundamental and sufficient conditions for consciousness. For example, theories includes the theories emphasising recurrent circuits (Edelman, 1992; Lamme, 2006), the theories highlighting the internal simulation, predictive mechanism, and generative models (Clark, 2013; Hohwy, 2013; Kanai *et al.*, 2019; Revonsuo, 2006; Seth, 2014, 2015), and theories related to multilevel view of consciousness (Jackendoff, 1987; Pennartz, 2015, 2018; Prinz, 2007). Notably, ICT is proposed based on the non-functional hypothesis. Notwithstanding, its implications for the functional aspects of a system well fit several functionalist proposals.

Regarding philosophy of mind, ICT connects several distinct arguments together. ICT can be seen as an identity theory because it assumes a fundamental relation between consciousness and information. Second, the implications of ICT tightly link consciousness to several cognitive functions in the context of evolution. This explains why people might intuitively have a functionalist point of view of consciousness. ICT emphasises that informational closure between scales of coarse-graining is critical to form NTIC processes in some stochastic systems. In this case, especially for the neural system, forming conscious processes at the macroscopic scales coincide with the perspective of emergentism. Finally, forming NTIC (conscious) processes through many-to-one maps, i.e., coarse-graining, implies multiple realisability of consciousness. As a result, ICT provides an integrated view for these arguments and is further capable of indicating how and why they are conditionally true.

So far, the current version of ICT is still far from completion. Further theoretical and empirical research is indispensably required for ICT to improve and solve several issues in the current version. Nevertheless, ICT offers explanation and prediction for consciousness science. We hope that ICT provides a new way of thinking and understanding neural substrates of consciousness.

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Author Contributions Statement

A.C. conceived and developed the theory. M.B. and A.C. contributed the mathematical formalisation of the theory. A.C., M.B, and R.K wrote the manuscript, based on a first draft by A.C. with extensive comments from Y.Y. All authors contributed to manuscript revision, read and approved the submitted version.

Conflict of Interest Statement

All authors were was employed by the company Araya Inc. The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

9 Appendix*

Let us assume that the system only observes a part of the environment state.

We can represent the part of the environment that we observe by the value of a function f applied to the environment state. In this case we get for the transfer entropy

$$I(S_{t+1} : E_t|S_t) = I(S_{t+1} : f(E_t)|S_t). \tag{19}$$

If the system only copies the observation we then get for the transfer entropy

$$I(S_{t+1} : f(E_t)|S_t) = I(f(E_t) : f(E_t)|f(E_{t-1})) = H(f(E_t)|f(E_{t-1}) \tag{20}$$

and for the mutual information

$$I(S_{t+1}; E_t) = I(f(E_{t+1}; E_t) = H(f(E_t)) \tag{21}$$

such that

$$NTIC = I(f(E_t); f(E_{t-1})). \tag{22}$$

This shows that whenever there is mutual information between subsequent observations a process that only copies the observations has positive NTIC. Note that any additional (internal) processing of the observation without reference to an additional internal state using a function g can only reduce this mutual information:

$$I(f(E_t); g(f(E_{t-1}))) \leq I(f(E_t); f(E_{t-1})). \tag{23}$$

However, for each such system there are systems that achieve higher NTIC. Take for example a "mirrored" and synchronized environment. In this case we have $S_t := E_t$ such that the transfer entropy vanishes

$$I(S_{t+1} : f(E_t)|S_t) = I(E_{t+1} : f(E_t)|E_t) = 0 \tag{24}$$

and the mutual information is equal to the mutual information between current and next environment state:

$$I(S_{t+1}; E_t) = I(E_{t+1}; E_t) \geq I(f(E_{t+1}); f(E_t)). \tag{25}$$

This shows that whenever the environment has itself more predictable dynamics than the observations there is potential for a predictive process to achieve higher NTIC than a copying system or any system that only processes its last observations without taking into account other internal memory.

———————- For a feedforward network with each layer computing just the identity:

$$NTIC = I(f(E_t), \ldots, f(E_{t-n+1}); f(E_{t-1}), \ldots, f(E_{t-n})) \tag{26}$$

$$= H(f(E_t), \ldots, f(E_{t-n+1})) - H(f(E_t)|f(E_{t-1}), \ldots, f(E_{t-n})). \tag{27}$$

For the mirror environment, if we use the history dependent NTIC (Bertschinger *et al.*, 2006) we get:

$$NTIC^{s,m} = I(E_{t+1}; E_t, \ldots, E_{t-n+1}) \tag{28}$$

To see that this is always larger or equal to the feedforward network note that the feedforward NTIC can be rewrittten:

$$\begin{aligned}
NTIC^{ff} &= I(f(E_t), \ldots, f(E_{t-n+1}); f(E_{t-1}), \ldots, f(E_{t-n})) && (29)\\
&= I(f(E_t); f(E_{t-1}), \ldots, f(E_{t-n})) + I(f(E_{t-1}), \ldots, f(E_{t-n+1}); f(E_{t-1}), \ldots, f(E_{t-n})|f(E_t)) && (30)\\
&= I(f(E_t); f(E_{t-1}), \ldots, f(E_{t-n})) + I(f(E_{t-1}), \ldots, f(E_{t-n+1}); f(E_{t-1}), \ldots, f(E_{t-n})|f(E_t)) && (31)\\
&= I(f(E_t); g(E_{t-1}, \ldots, E_{t-n})) + I(f(E_{t-1}), \ldots, f(E_{t-n+1}); f(E_{t-1}), \ldots, f(E_{t-n})|f(E_t)) && (32)\\
&= I(E_t; E_{t-1}, \ldots, E_{t-n}) \underbrace{-B + I(f(E_{t-1}), \ldots, f(E_{t-n+1}); f(E_{t-1}), \ldots, f(E_{t-n})|f(E_t))}_{\leq 0} && (33)\\
&\leq I(E_t; E_{t-1}, \ldots, E_{t-n}). && (34)
\end{aligned}$$

$$\begin{aligned}
I(X;Y) &=_? I(f(X), X : g(Y), Y) && (35)\\
&= I(X : g(Y), Y) + I(f(X) : g(Y), Y|X) && (36)\\
&= I(X : g(Y), Y) && (37)\\
&= I(X : Y) + I(X : g(Y)|Y) && (38)\\
&= I(X : Y) && (39)
\end{aligned}$$

$$\begin{aligned}
I(X;Y) &= I(f(X), X : g(Y), Y) && (40)\\
&= I(f(X) : g(Y), Y) + I(X : g(Y), Y|f(X)) && (41)\\
&= I(f(X) : g(Y)) + I(f(X) : Y|g(Y)) + I(X : Y|f(X)) + I(X : g(Y)|Y, f(X)). && (42)
\end{aligned}$$

$$I(f(X) : g(Y)) = I(X;Y) - I(f(X) : Y|g(Y)) - I(X : Y|f(X)) - I(X : g(Y)|Y, f(X)) \tag{43}$$

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Figure Legends