Response to Reviewers Rev^1

March 17, 2020

Reply to Editor

Q1: In addition, I have a question. if we view molecules as coarse grains of elementary particles, would the phenomenon of molecular recognition have high NTIC and thus be conscious?

A: Hi Prof. Hoffman, Thank you for your attention to our manuscript and your interesting question. There is no question that molecular complexes are coarse-grainings of molecules via molecular recognition. Based on our hypothesis, if the dynamics of a molecular complex is an NTIC process, the information closure theory of consciousness (ICT) would claim that the molecular complex has a certain degree of consciousness. Therefore, to your question, it is theoretically plausible under the framework of ICT. We speculate that it may be easy to find informationally closed molecular complexes (isolated complexes) but may not be easy to find ones forming NTIC processes. Nevertheless, with well-defined mathematical definition, this is an empirical and testable question to ICT. We look forward to learning any self-assembly process forming NTIC at molecular scales in the near future.

Reply to Reviewer 1

Q1: Regarding the NTCI measure:

a) Bertschinger et al. 2006 define informationally closed as $J_t(E->Y)=0$, but this is not a requirement for NTIC. Meaning, a positive NTIC measure does not entail that $J_t=0$. $J_t=0$ is only true if the NTIC is equal to $I(Y_{t+1};E_t)$. In what sense does it correspond to non-trivial information closure then? (see also my concern #2, maybe that is related) As defined in eq. 6 a video camera might have very high NTIC if it records a natural scene, even though it is in no way informationally closed from the environment.

b) Is $NTIC_t$ state dependent or not? As capital letters are used I assume it is based on (conditional) mutual information measures across one time step but averaged over the possible states of the system at time t and t+1, so state distributions. But which distributions are used to compute $NTIC_t$? The stationary joint distribution of states at t and t+1? It cannot be just some observed measure, because then the level of consciousness would depend on how long the observation is. Moreover, if $NTIC_t$ is not state dependent, then the Reflex example on p. 10 is not intuitive. Because the system (brain) is the same and awake whether it behaves reflexively or not, so while the content may depend on the type of action, the $NTIC_t$ (level) would stay the same.

A:
a) Considering Eq.7, it is true that the transfer entropy term $J_t(E->Y)=0$ is not required for $NTIC>0$. It is possible to have a high degree of NTIC when $J_t(E->Y)>0$, i.e. the process is not completely closed.
However, based on the setting in both Bertschinger et al. 2006 and our Section 2 (at Line 105), Y_{t+1} is determined by both Y_t and E_t. Simply increasing $I(Y_{t+1};E_t)$ without closedness (e.g, copy the information in sensory signals to the process such as the case in the video camera example), the transfer entropy term $J_t(E->Y)$ should increase at the same rate and cancel out the increment of $I(Y_{t+1};E_t)$ resulting low NTIC. Namely, keeping high closedness, i.e. minimising $J_t(E->Y)$, is crucial to increase NTIC even though $J_t(E->Y)>0$.

In our current version of ICT, we consider the level of consciousness corresponds to the degree of NTIC of a process. Therefore, a conscious process does not have to be completely closed. However, a high degree of closedness is crucial to have a high level of consciousness.

b) Thank the reviewer for this outstanding question. We entirely agree that state-dependent measurements are essential to describe the dynamics of conscious experience. In fact, we now are working on state-dependent formulations for the next version of the ICT. In contrast to the current version, this work involves point-wise informational measures and certainly require more space and discussion. Therefore, we prefer to address the state-dependent version of ICT in future studies and keep the first version of our theory simple.
We appreciated that the reviewer pointed this out. We have added a short paragraph about this issue.

> **Line 596:**
> *" In this article, we do not use a state-dependent formulation of NTIC in the current version of ICT. 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 in the next version of ICT. "*

Q2: Hypothesis and Implication 3: Why is it crucial that there is an underlying X with respect to which Y is a C-process? Does Y being informationally closed with respect to X imply that Y is also informationally closed with respect to E, i.e. $J_t(E-Y)=0$? I don't think that could be true for the brain, or part of it really. My brain's next state, at whatever level, certainly depends to some degree on unpredictable sensory inputs from the environment. In the end, is $I(Y_{t+1};E_t|Y_t)=0$ required for consciousness or not? (see point 1a). In other points in the manuscript this does not seem required, e.g. p. 10 "If a process is not informationally closed, the degree of NTIC is low resulting in low or no consciousness".

A: Because X is the micro-level of the universe, any coarse-graining of X (including E and S) should have equal or less information about Y than X, i.e. $I(Y_{t+1};X_t|Y_t) \geq I(Y_{t+1};S_t|Y_t)$ and $I(Y_{t+1};X_t|Y_t) \geq I(Y_{t+1};E_t|Y_t)$. Therefoe, Y is informationally closed with respect to X implying that Y is also informationally closed with respect to S, E, and all other coarse-grainings of X. As explained in Question 1a, it is not required for NTIC processes to be completely closed. Therefore, the closedness of Y with respect to X $I(Y_{t+1};X_t|Y_t)$ serves as the lower bound of the closedness of Y to any other processes. For this first exposure of our theory, we did not discuss NTIC in the context of the temporal coarse-graining. It is true that we certainly encounter some degree on unpredictable sensory inputs from the environment from time to time. Therefore, NTIC should be higher for finer temporal scales than for coarser temporal scales. We also speculate that the temporal coarse-graining is related to the speed of "stream of consciousness" and will address this issue in our future studies.

Q3: Exclusion or no exclusion? The authors state multiple times that "every process with a positive non-trivial information closure (NTCI) has consciousness." (p.3, and also p.12). a) Yet, Figure 4 is ambiguous in the sense that the maximum somehow seems important, while actually all levels should give rise to separate experiences. I don't see how ICT without something like exclusion (IIT style) would indicate that the maximum should correspond to human consciousness. It could just be any one out of many consciousnesses. b) p. 14: comparison to IIT: what does ICT say about different sets of variables at the same level. There might well be multiple ways to partition X into S and E, with many overlapping S's. Would those all be conscious? They would not be informationally closed from each other but they could all fulfill the requirements in the Hypothesis. It seems like finding the maximum within a level over the possible sets of elements/variables is a necessary step to identify boundaries (I think also Krakauer does that across sets of variables, but not 100% sure)

A: We do not impose the exclusion criterion in ICT. Instead, the concept of informational closure already involved the notion of individuality and was used to identify the system-environment distinction (Bertschinger *et al.*, 2006) and level identification (Pfante *et al.*, 2014b) in system theory (however not complete, please see our discussion at Line 551). In Bertschinger *et al.* (2006),

It is true that if we assume a process Y is NITC with respect to E. Every subset of Y can have different degrees of NTIC with respect to E as well. However, it is important to note that the subsets are not "other consciousnesses". Rather, they are subspaces of this conscious process Y.

[[I this this is still bad]]

Q4: Feedback and memory: p. 11. If $NTIC > 0$ is sufficient and true information closure is not required, then feedfoward networks can be conscious according to ICT. Also, in that case, memory is not necessary, as the video camera would have $NTIC > 0$ as long as it records from a stable environment. In that case $I(Y_{t+1}, Y_t) > 0$ and $I(Y_{t+1}, Y_t|E_t)$ is small. This issue here is that having information about the next state does not imply that there is any causation, so if Y_t is highly correlated with E_t and E_t causes Y_{t+1} then NTIC is high. (Thus the IIT emphasis on causation). If somehow the fact that Y must be informationally closed wrt X does the heavy-lifting here that should be made more explicit (see above).

Q5: Does ICT imply that one is unconscious while dreaming? In that case $I(Y_{t+1}; Y_t|E)$ should almost be identical to $I(Y_{t+1}; I_t)$ and thus lead to NTIC approx. 0.

A: We want to emphasise that not all the processes in the neural system are NTIC processes. This is evident since some processes in the neural system are not informationally closed. They only passively react to sensory inputs or other processes of the neural system.

To the conscious (NTIC) process, the rest of the neural system is considered as part of the environment. This notion is shortly indicated at line 196 in our original manuscript. There is no doubt that these processes are still active during sleep and dreaming. We speculate that, during dreaming, the neural system can stably form the NTIC process with respect to its environment, i.e. other parts of the neural system. However, at the current stage, this is mere speculation so we restrained ourself from making the statement in our manuscript. However, we thank the reviewer for bringing up this important question. We believe that this is still worth mentioning. We have added a short paragraph as follows:

> **Line 570:**
> *"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."*

Finally, we believe that this is also an empirical question that can and should be tested in future studies.

Q6: Minor:

1. "contributions to the field" This section is just a copy paste from the abstract and thus not necessarily helpful. Not sure though what the purpose of this section is meant to be by Frontiers.
2. Introduction: "We currently lack a theory... " IIT and the geometric theory of consciousness (Fekete et al.) have proposed solutions. So there are theories. The following paper should be of interest and should probably be cited: Fekete T, van Leeuwen C, Edelman S (2016) System, subsystem, hive: Boundary problems in computational theories of consciousness. Front Psychol 7:1041.

3. y_t corresponds to the content. I would argue that an activation state, without taking the system or relation between elements etc into account is meaningless and cannot capture/explain the structure of an experience. Though this issue can be dealt with at a later time.

A:

1. It's true that we were also confused about it during submission. We have modified this as follows:
   [["contributions to the field"]]

2. Thank the reviewer for the reminder. We have modified our manuscript and cited the relevant references.

   Line 80:
   Original:
   "We currently lack a theory to identify the scale which conscious processes correspond to."

   Revised:
   "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 (please also see the discussion in Fekete et al. (2016))."

3. We agree with the reviewer's comment. In fact, in ICT, we do not differentiate states of processes between activation and relation. Take neural networks as an example, activation and structure states of a neural network should be both considered. After all, they are all just parameters of the process of the neural network. The only difference between the two groups of the parameters is the temporal scales of the parameter changes. States of activation may have more rapid dynamics than states of relation. In ICT, this is crucially related to the coarse-graining at the temporal domain which we did not address in this article but can be easily generalised in the future versions of ICT.

Do we need to write something in the main text?

Reply to Reviewer 2

Q1: I had a few problems in reading the paper, which I think should be addressed (especially the first) before the paper is published. For detailed notes on these see below.

1. The coarse-graining idea seems undefined in critical ways, but the paper reads as though it is well-defined. So maybe the authors have compressed too much detail? In the formalism presented it is unclear what coarse-graining (or information closure to other grains) amounts to. With this lack of detail, it is then unclear to me why intermediate maxima in IC are a plausible result (why does IC not just decline with progressive coarse graining).
2. The idea of 'simulation'. This is a more minor point but I would appreciate if the authors could be clearer on this. It is arguable whether or not consciousness simulates anything (e.g. see Hoffman's interface theory); and some of the assertions the authors make re simulation seem unfounded anyways. But it could be that they mean something different or subtle (that consciousness is linked to or represents or etc the environment)
3. There were several other assertions that stood out to me as strange or wrong, but could be a matter of explanation or ignorance on my part (the feedforward system, the cut-apart system). Either way some more explanation would be good.

A:

1. In this article, the definition of coarse-graining is our "Definition 1" (line: 176). Coarse-graining is simply a function which maps a stochastic process X with state space $\mathcal{X}$ to a stochastic process Y with state space $\mathcal{Y}$. As we explained in Footnote 2, functions in the mathematical sense used here are always either one-to-one or many-to-one. We do not constrain ICT to be applied to any specific classes of coarse-graining. Thank the reviewer for proposing the question about the relationship between NTIC and scale of coarse-graining. We currently know that NTIC is not a non-monotonic function of the scale of coarse-graining. Some coarse-grainings lead to higher NTICs for macroscopic than microscopic processes. However, we are just starting the research on this relationship, and have not yet had a systematic understanding of it. This work may involve the technique of partial information decomposition and related research fields. We agree that our original claim about existing a intermediate maxima in NTIC was too strong.

   We hope to address this question in future research.

   We emphasise the non-monotonic relation between the scales of coarse-graining and the degrees of NTIC. However, we do not exclude the possibility that there exist multiple NTIC picks across scales of coarse-graining of a process. This implies that we do not exclude the possibility that there exist multiple high conscious processes at different scales. (However, due to IC, conscious processes are not able to know the existence of each other.

   Line 245:
   Original:
   " It is important to note that NTIC can be a non-monotonic function of the scale of coarse-graining. We saw above that not sufficiently coarse-grained variables have low values of NTIC. On the other hand, overly coarse-grained macroscopic variables also result in low values of NTIC. For example, in an extreme scenario, when all microscopic states map to a single macroscopic variable, the macroscopic level does not have any information capacity and thus cannot have high mutual information across time steps. Therefore, only processes at a certain level of coarse-graining in the neural system can form a high degree of NTIC (Fig. 4). ICT indicates that human consciousness occurs at the level of coarse-graining where higher NTIC is formed within the neural system. "

   Revised:
   " It is important to note that NTIC can be a non-monotonic function of the scale of coarse-graining. Insufficiently coarse-grained variables could lead to lower values of NTICs at micro than macroscopic processes. On the other hand, overly coarse-grained macroscopic variables also result in low values of NTIC. For example, in an extreme scenario, when all microscopic states map to a single macroscopic variable, the macroscopic level does not have any information capacity and thus cannot have high mutual information across time steps. Therefore, processes at certain levels of coarse-graining may have higher values of NTIC than other levels (Fig. 4). ICT suggests that human consciousness occurs at the level of coarse-graining where higher NTIC is formed within the neural system. "

2. **[[TBD]]**

Q2: The English is not perfect and needs some good proofreading, though it was understandable throughout.

A: ____

What should we deal with this?

Q3: On line 182, defining C-processes as cases where 'Y is informationally closed to X'. This is now information closure in the sense of coarse-graining, but no such thing has been defined yet? Is it supposed to be so trivial that it is not required to make it explicit? To this point, closure is defined entirely in terms of system with respect to environment.

Basically, I am not sure whether closer between scales is a matter of same-time (e.g. $I(Y_{t+1}; X_{t+1})$) or across-time interactions ($I(Y_{t+1}; X_t)$). Or could it be both?

A: We followed a common setting of coarse-graining (e.g. Pfante *et al.* (2014b)) which does not and should not take time $Y_t = f_Y(X_t)$ (in Definition 1). Coarse-graining is merely a function which maps microstates of a system to macrostates, and the microstates and the macrostates are simply different level of descriptions of a system. Following this setting, the definition of information closure (flow) $J_t(X \to Y)$ can also be applied in the sense of coarse-graining.

We understand that this may lead to confusion for our readers. We have added the following sentence to make this point explicit.

> **Line 189:**
> *"Note that we applied the same definition of information closure (Eq.1) to processes at different coarse-grained levels (Pfante* et al.*, 2014b)."*

Q4: On line 241: ".. not sufficiently coarse-grained variables have low values of NTIC", this is phrased as though it is necessarily true (and also that "we saw above", though I do not see above where this is justified), but is it?

At the very finest grain, wouldn't even all the most 'stochastic' dynamics of a system be accounted for by prior states of the system, or by the environment? Why wouldn't we assume that NTIC *only decreases* as the system is coarse-grained (as number of elements/states is decreased), for similar reasons as it must be zero at a 1-element 1-state system as the authors note? This seems an important point to be very clear on. . .

A: **[[The reviewer is right?]]** Thank the reviewer for this critical comment. It is true that NTIC a monotonic function of scales of coarse-graining. NTIC can increase or decrease when the grains are coarser. We are currently still working on the relationship between scales and NTIC. We will systematically address NTIC and functions of coarse-graining in our following studies. Further more, in our current analysis, it seems that this is also related to informational synergy and redundancy. We aim for presenting the core concept of ICT in this article. The reviewer's critical question is on our list of future work. **[[Need to change the text a lot!!]]**

Q5: on line 263: "NTIC processes encodes environmental information in its state. This suggests that a NTIC process can be considered as a process that simulates the environmental dynamics.“

Why does encoding suggest simulation? An encoding *could* be a simulation, but it could well be nothing like a simulation, if we understand simulation to mean something like an imitation or reconstruction of some structure or dynamics. Two totally different environmental situations could potentially be encoded in exactly the same way (eg. as a string of 1s and 0s).

The 'simulation' notion is brought up again in section 5.2 (line 344), citing Bertschinger et al, though I do not find the idea in that paper.. I think authors need to be clearer on what they mean by 'simulation' to make this point.

A: Thank the reviewer for this mindful comment. Our wording indeed is not clear. The notion of simulation is the same as the 'Modeling' case on Page 4 in Bertschinger *et al.* (2006):

> *"B2) Modeling: The system reaches synchronization and internalizes the correlations observed in the environment by building up own structures."*

To avoid the confusion We have revised the following sentence, changed "simulation" to "modeling", and added the reference.

Line 268:
Original:
" Importantly, NTIC processes encode environmental information in its state. This suggests that a NTIC process can be considered as a process that simulates the environmental dynamics. "

Revised:
" 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. "*

Q6: line 306: "Blindsight patients... make above chancel-level visual judgments without having any conscious perception about visual stimuli" I am not sure this characterization of blindsight is correct, it may be a matter of the phrasing. It could be - or probably is - the case that 'blindsight' patients always have some conscious experience of what drives their correct responses, but that the "visual character" of these experiences is degraded or missing. (Overgaard, Experimental Brain Research 2011) for a specific example (Mazzi, Bagattini, Savazzi; Frontiers in Psychology, 2016)

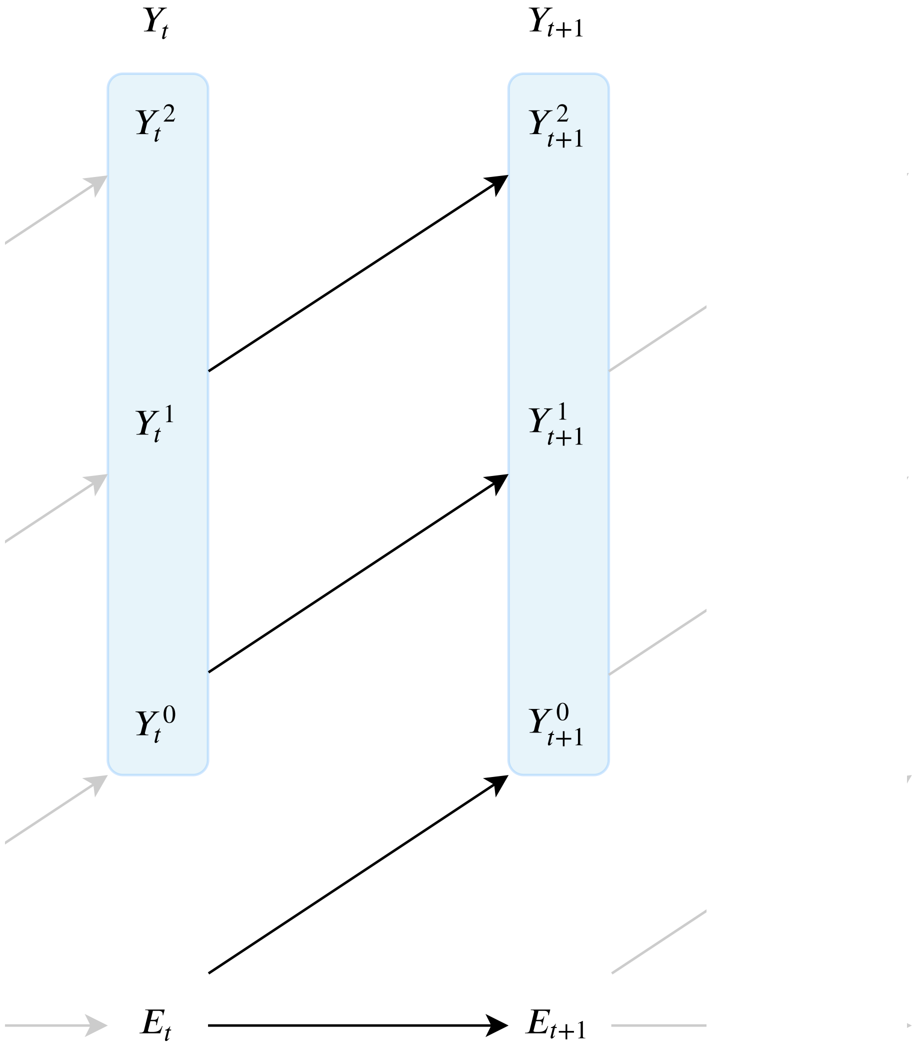
A: Thank the reviewer for the clarification. Yes, we specifically wanted to address the visual character of their experience. We agree that some patients still preserve some forms of conscious experience. We have changed our sentence and cited the relevant references as follows:

Line 310:
Original:
" Blindsight patients are able to track objects, avoid obstacles, and make above chance-level visual judgements without having any conscious perception about visual stimuli. "

Revised:
" 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)). "

Q7: on Line 316: On the issue of a feedforward network, the current state of a feedforward network with more than one layer is certainly driven by its own past states! So, mutual information of a feedforward network over a time lag should not be zero, unless I am misunderstanding something here? At the same time, I can see a version of the authors' argument here - for a unit in a feedforward network with depth (distance-from-input) of N, a time lag of N time steps would always account fully for the states of the element. Is this the idea?

A: Thank the reviewer for proposing this interesting and valuable comment.
We can consider a simple case in which a feedforward neural network Y consists of three layers, Y^0, Y^1, and Y^2. Y^0 receives sensory input from the environment E. Each layer Y^i_t passes information to the next layer Y^{i+1}_{t+1} with a constant time cost Δt as showed in the following figure.



Because Y_t^0 determines Y_{t+1}^1 and Y_t^1 determines Y_{t+1}^2, it is true that the mutual information $I(Y_t; Y_{t+1}) \geq 0$. However, E_t only influences Y_{t+1}^0 at time $t+1$. Therefore

$$
\begin{aligned}
&I(Y_t; Y_{t+1}|E_t) = I(Y_t; Y_{t+1}) && \text{and} \\
&NTIC_t(E \to Y) = I(Y_{t+1}; Y_t) - I(Y_{t+1}; Y_t|E_t) = 0
\end{aligned}
$$

Therefore, a feedforward network passively driven by input signals should have zero NTIC even though when time step (temporal coarse-graining) is small.

I don't think I answer this question well. Do we need to add anything in the main text?

Q8: on line 441: under the 'Prediction after system damaged', it is suggested that ICT predicts cutting a system in half would render both halves unconscious. But this would only be the case if neither half contains its own C-processes, yes? Since ICT allows that many C-processes can exist at the same time, it would have to be some special case for this prediction to hold true. So it seems to me the prediction is actually similar to that of IIT.

A: Thank the reviewer for this considerate comment. The reviewer is correct. This prediction is under an assumption which we did not explicitly specify in our last version. We assume that we have one conscious (NTIC) process involving information in both brain hemispheres. Namely, the process is informationally closed only when we consider the information in both hemispheres. We agree that if both hemispheres have their own NTIC proceess ICT should predict no change of conscious experience before and after cutting. Cutting should not make any difference because they are informationally closed with respect to each other. We also agree that this prediction is relatively premature. However, we also acknowledge the strength of all computational theories of consciousness. The reviewer's question is empirical to us under formal mathematical formulations of ICT and IIT. Systematical comparisons between model predictions can be done by rigorous modelling studies in the future.

[[The original paragraph has been changed as follows: lline 443:]]

Q9: Line 540: the theory doesn't really seem to intend to solve the hard problem(s) at all, much less "completely solve". I was expecting the problem of dreaming to come up in the last section (maybe along with SMC for which it is a serious problem). When dreaming the information between environment and the system is virtually zero; is this a problem for ICT? Also, more specific phenomena like the eigengrau - if you take away all visual input, for long enough, I do not lose my visual experiences - rather they take on a special state. Does ITC need to accept the possibility that even *trivial* IC can be a conscious process?

A: ICT is our first attempt to approach the hard problem of consciousness. We hope that ICT and our following works can establish an informational perspective on conscious experience. Instead of solving the hard problem of consciousness, we more look forward to mathematically determining whether the hard problem can be solved or not by information theory. However, because the relevant discussion is clearly outside the scope of this article, we prefer not to discuss the hard problem here.

We want to emphasise that not all the processes in the neural system are NTIC processes. This is evident since some processes in the neural system are not informationally closed. They only passively react to sensory inputs or other processes of the neural system.

To the conscious (NTIC) process, the rest of the neural system is considered as part of the environment. This notion is shortly indicated at line 196 in the original manuscript. There is no doubt that these processes are still active during sleep and dreaming. We speculate that, during dreaming, the neural system can stably form the NTIC process with respect to its environment, i.e. other parts of the neural system. The same idea can be also applied to phenomena like Eigengrau. However, at the current stage, this is mere speculation so we restrained ourself from making the statement in our last version of the manuscript. However, we thank the reviewer for bringing up this important question. We believe that this is still worth mentioning. We have added a short paragraph as follows:

> **Line 570:**
> *"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."*

Finally, we believe that this is also an empirical question that can and should be tested in future studies.