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Universitat Autònoma de Barcelona

Facultat de Psicologia

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Development of a first proposal on the Integrative Neurobiological Model of Consciousness through a phylogenetic perspective on the nervous system

EV2a: EXECUTIVE SUMMARY

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Marçal Castán Sogas

BACHELOR'S DEGREE FINAL THESIS
2019-2020

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Target Agents of the Executive Summary

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Considering the multidisciplinarity of our work, that produces a philosophical argument through neurobiological scientific evidence, and taking into account that proposes the concept of an integrative model to understand consciousness (with a skeleton of operable variables, but poorly defined in mathematical terms) we estimate that the following natural step on this work is to **establish a multidisciplinary research group** dedicated to providing a deeper development to the model with the common effort of different disciplines as physics, computational science, neurobiology, psychology and philosophy. To reach this, we propose that **the target agent of the executive summary** must be a decisive part of an institution capable of putting together the necessary economic, material and human resources to found the multidisciplinary research group and to establish a scientific research program. In the public Catalan ambit, we could think in **directives of institutions like CSIC** (Consell Superior d'Investigacions Científiques) and every university on its horizon. In the private ambit, a directive of a **business with powerful departments of I+D** combining scientific and computational research, with interest in transhumanist technologies or in virtual agent development, could fit the criteria to be a key agent of our executive summary.
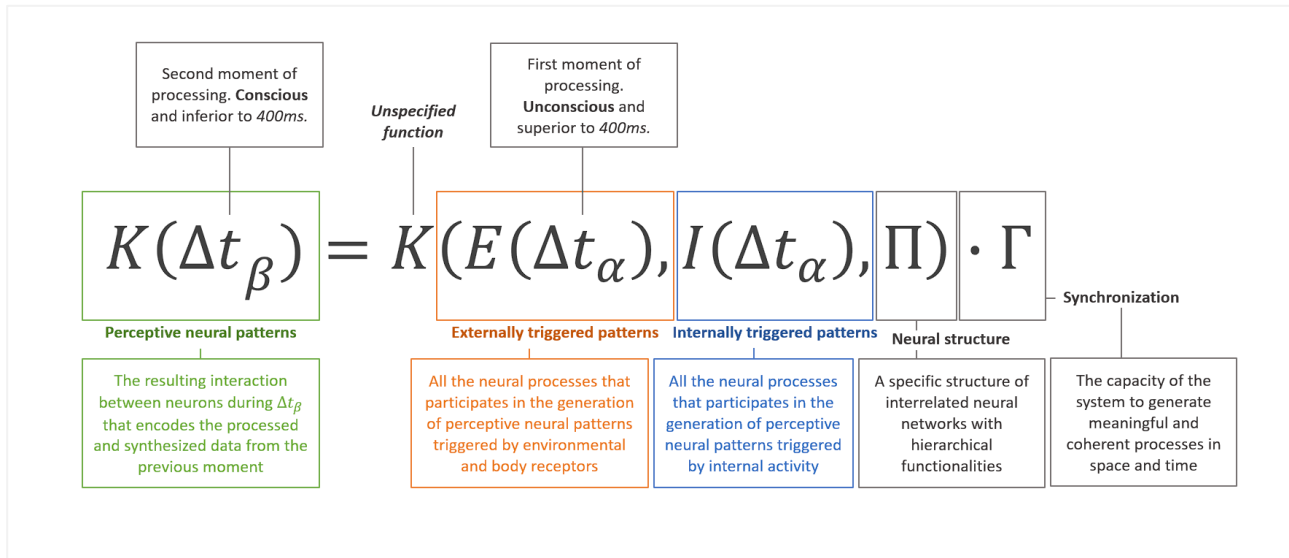
Words: 1498

INTRODUCTION

The unobservability of experience in a third-person perspective, that apparently limits the scientific approaching over the conceptualization and understanding of consciousness, fertilized a field where neo-dualist theories are growing up with philosophical and neuroscientific support, as well as anthropocentric top-down approaches are restricting the debate to humans. Considering this state of the art, we identified the necessity to strengthen the strict scientific physicalism, especially based on what neurobiology can explain about the nature of the subjective experience, maintaining a phylogenetic perspective on the evolution of the nervous systems.

To do that, we selected three cutting-edge neuroscientific theoretical frameworks related with consciousness and experience: The **Neurobiological Naturalism** from Dr Todd E. Feinberg and Dr Jon M. Mallatt, that sets a proposal on the neurobiological features of an organism to be conscious, the **Two-Stage Model** from Dr Michael H. Herzog and his colleagues, that proposes a real-time perceptive mechanism based on the experimental evidence, and the **Neuronal Global Workspace** of Stanislas Dehaene and his colleagues, a proposal based in the real-time processes of the brain, as well as some crucial neural structures.

Through the filtering and selection of the trunk variables of each model, and the development of a set of foundational axioms, we produced our own model: The **Integrative Neurobiological Model of Consciousness** (INMC), that tries to explain *what is consciousness,* with the combined potential of the three previous approaches. The INMC presented the capacity to be formulated, and every variable of it showed mutually dependence (see Figure 1).

The **neural structure of the INMC** contemplates the necessity of **different functional networks**: topographic single-sense structures, multisensory integration structures, salience coding structures, valence coding structures, memory structures, and perception coding structures.

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Figure 1. INMC formula

$$K(\Delta t_\beta) = K(E(\Delta t_\alpha), I(\Delta t_\alpha), \Pi) \cdot \Gamma$$

- Second moment of processing. **Conscious** and inferior to *400ms.*
- *Unspecified function*
- First moment of processing. **Unconscious** and superior to *400ms.*
- Synchronization

Perceptive neural patterns — The resulting interaction between neurons during Δt_β that encodes the processed and synthesized data from the previous moment

Externally triggered patterns — All the neural processes that participates in the generation of perceptive neural patterns triggered by environmental and body receptors

Internally triggered patterns — All the neural processes that participates in the generation of perceptive neural patterns triggered by internal activity

Neural structure — A specific structure of interrelated neural networks with hierarchical functionalities

The capacity of the system to generate meaningful and coherent processes in space and time

Excepting the *Synchronization* variable, that performs a restrictive role on the expression, the other variables are operable sets of minor processes or structures that remit to the neuron as the minimal unit: located in a three-dimensioned space, synapsed with other neurons and activated during specific lapses of time. The full work of mathematical operationalization includes every hierarchy of every set.

Finally, the INMC, once developed, and referring directly to the statements of its theoretical framework, implies the following hypothesis:

Working hypothesis of the INMC

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- **Null Hypothesis:** Consciousness is an emergent property
- **First Hypothesis:** Consciousness is a process that brain does
- **Second Hypothesis:** Consciousness is at least a vertebrate function

METHOD

To put under test the hypothesis **we selected the lamprey fishes** (considered one of the first vertebrates) as an **animal model** to compare the INMC with a phylogenetical crucial organism that according to the Neurobiological Naturalism, could be conscious. Once the fitness between the animal model and the INMC have been tested, we searched for **differential criteria**: this is, criteria that authors without relation with our referential theoretical frameworks proposed to consider the existence of consciousness in animals. The third step has been the crossed comparison between the INMC, the lamprey brain and the considered crucial features for **consciousness in humans**. This allowed us to test at the same time the validity of the model and the possible presence of consciousness in lampreys, first ensuring its mutual fitness, second testing the animal model with alternative criteria, and finally testing the animal model and the INMC with criteria applied on clearly conscious organisms.

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The evidence research in every step has been realized within a **qualitative systematic review** using the following databases: NCBI and PubMed, ResearchGate, PsycInfo, Scopus, and scientific editorials and journals: Elsevier, Frontiers in Psychology, MIT Press, Scientific American, Nature and Science. The **selection conditions** for the referenced papers have been: (1) English as the only language admitted (2) at least 80% of the references must be from 2009 to actuality when related to the field of neuroscience and (3) the observational data must be extracted from papers non-related to the theoretical framework of the INMC.

RESULTS AND DISCUSSION

The neurobiological evidence collected confirms the presence of **topographic sensory structures** in lamprey brains, as well as **multisensory integration structures**. Our minimal-vertebrate model also presents **salience coding structures** on its tectum, as well as **memory structures** based on its pallium. The presence of reward-seeking and misery-fleeing behaviours on the animal allows us to infer its neural **valence coding structures**. Moreover, thanks to recent studies on the neurobiology of lamprey, as well as experimental evidence of perceptive illusion on three species of fishes, we can infer the presence of a **perception coding structure** on its brain. Finally, the lamprey also presents neural supporting systems that allows the **spatiotemporal synchronization** of the electrochemical activity.

In the second test, the lamprey showed fitness with all the 11 collected variables, based on the criteria of other authors to infer consciousness in animals. In the final test, the INMC and the lamprey fishes showed high compatibility with all the 10 collected variables, based on the criteria of other authors to infer consciousness specifically in humans. Although **the null hypothesis cannot be refuted** because of the ontological problem of experience, the amount of evidence allows us to defend that **consider consciousness as a process that the brain does** until proven otherwise, and that **consider consciousness at least a vertebrate function** until proven otherwise is the most parsimonious, simpler and ethical, as well as the unique falsifiable approach by the time.

CONCLUSION AND IMPLICATIONS

Concluding, the INMC proposes that consciousness is a **continuous process** that the brain does, and that can be found in at least every vertebrate. The continuity of the process implies a **loop** where every actual perception is the result of the previous neural activity correspondent to the anterior perception, with new internal activity, and the new entrance of external stimuli (see Figure 2).

This implies that the qualities of experience are only **convictions** of the same system that is generating it. Convictions that are trapped in a continuous loop of cause-effect, without any necessity of emergent properties to explain it. The unique reality that can exist by a perceptive system is the perceived reality, or in other words, **the experience and the experiencing subject are the same.** Thus, there is no necessity to establish a gap between *the redness of red* and the neural processes that encode for the red experience, because the redness of an object is an inescapable conviction of the system, a neural classification spatiotemporally determined that only have sense inside a loop of many processes that contextualizes and signify its data.

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At the moment that we conclude that there is nothing essential or permanent in us but the convincement of the system about its agency, that is also a functionality based on the neural architecture and processes, we can suggest that **consciousness could theoretically be replicated**, considering that a replicated system will share all the same convincements.

Figure 2. The INMC Loop
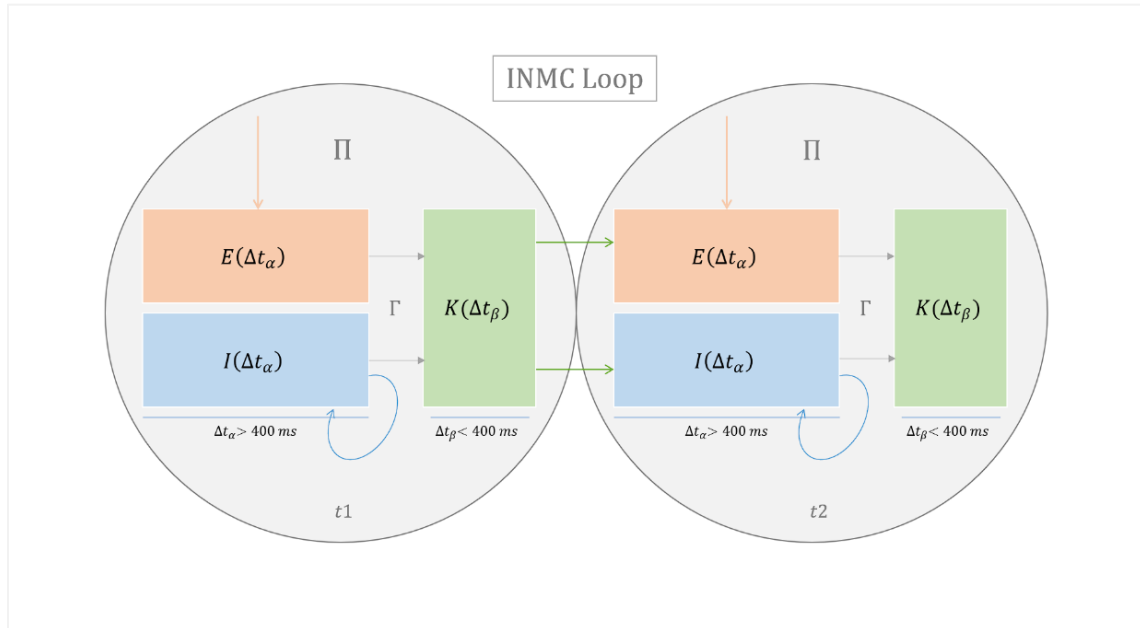
But the applicability of the INMC is not only philosophical. Its formula is conceived to be a skeleton of robust variables that are major sets of other lesser components, that at the same time are sets of other lesser components, with a very origin on the neuron itself. Thus, the INMC expression is not an operable formula but **a template especially thought to be converted in algorithms**, this is, to provide a background for programming experiments, with applicability on virtual agent development, artificial consciousness development and computational neuroscience improvements with applications on understanding perception (therefore, with clinical possibilities). Finally, the INMC also open an ethical debate. Its scientific development could contribute to the revision of our actual animal treatment politics and the increase of the consideration of the suffering, in at least, every vertebrate specie.

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EV2b: PRESS RELEASE

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Marçal Castán Sogas

BACHELOR'S DEGREE FINAL THESIS
2019-2020

The Mind-Body Problem Unveiled: an integrative neurobiological approach could close the gap between the experience and its neural correlates

The findings also suggest that every vertebrate in the animal phylogeny could be conscious

PRESS RELEASE

Barcelona, 21 March 2020

"What consciousness really is?" is an ancient question that remits to the concept of mind, and the unbridgeable problem that arises when we try to explain the subjective experience through the observation of the neural processes. *The redness of red*, for us, the experiencing subjects, is clearly something different than an intricated chain of firing neurons. We live with the conviction of the existence of the properties that we feel and observe, and to think on the contrary is to think against common sense. But what if I told you that, for the neurobiology, *there is no reason to consider these properties something different* than neural processes?

The recently developed Integrative Neurobiological Model of Consciousness propose exactly this statement. Through the integration of three promising and cutting-edge neuroscientific approaches, the model has been able to provide a snapshot of what consciousness could be, and the scientific evidence suggests that there is no need to consider it more than a process that the brain does. This is possible because the brain is an organ that evolved through the animal phylogeny to adapt the behaviour of the mobile organism to its environment: the bodies acquired receptors of the physical and chemical events around and inside them, and the receptors had been attached to specific neurons. With a brain that represents the activity of each receptor with a single neuron, more and more functionalities are possible inside it. When many senses are integrated to generate global maps of the situation, the resulting experience is not a simple sum of inputs: there are many possibilities to interpret the situation, and the brain actively decides what is the best one. *The brain actively builds the reality*.

This is, thanks to a systematic qualitative review of recent neuroscientific evidence, that proved the fitness of the model with more than 20 behavioural and neurobiological variables based on consciousness, the INMC suggests that the features that allow consciousness in humans are also present in lamprey fishes. This implies, as it is shown in the figure, that every vertebrate in the animal kingdom could be conscious.

The Vertebrate Evolving Tree

MYA: Million Years Ago. The moment where a branch of the evolving tree is split up.
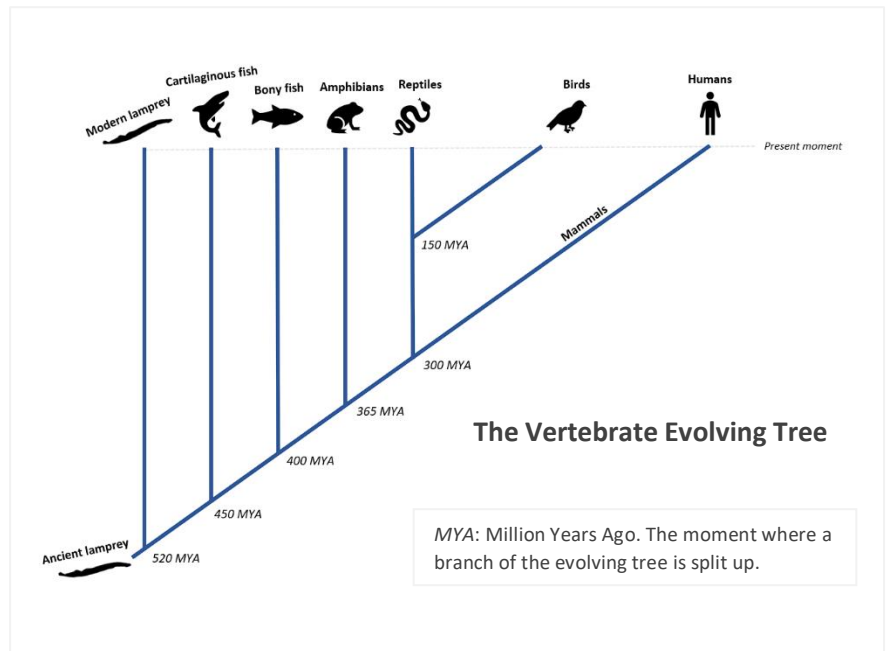
But, besides the ethical implications of these findings, the INMC also suggest that consciousness, as a process sustained in the physical known laws, could eventually be developed in artificial contexts, or inclusive could be eventually replicated. Although this science-fiction statement, the increasing interest in transhumanist technologies and the artificial agent development is a real business of the present, and the INMC makes a (tiny) contribution to advance in the computational conceptualization on its big protagonist. Even though its weaknesses, the INMC is an invitation to unite efforts between scientific disciplines to understand better the unique window to the world that we have: our very subjective experience.

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Marçal Castán Sogas

Supervised by Dr Gemma Guillazo Blanch,
Department of Psychobiology and Methodology,
Universitat Autònoma de Barcelona

BACHELOR'S DEGREE FINAL THESIS
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To my mother, Teresa
The very origin of my consciousness

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Development of a first proposal on the Integrative Neurobiological Model of Consciousness through a phylogenetic perspective on the nervous system

Marçal Castán Sogas
Psychology Degree & Minor in Human Evolution and Paleontology. Facultat de Psicologia, Universitat Autònoma de Barcelona

Abstract

The actual state of the art over the scientific and philosophical problem of consciousness includes approaches based on new forms of dualism. Considering the necessity of strengthening the eliminatory and strict physicalism, we developed a model of consciousness that integrates three neurobiological cutting-edge theoretical frameworks. The interlace of the Neurobiological Naturalism, the Two-Stage model of perception and the Neuronal Global Workspace, as well as own proposals of characterization and operationalization of the variables involved in consciousness, provided us two working hypotheses: consciousness is a process and is at least a vertebrate characteristic. The hypotheses have been tested through a triple comparison based on neurobiological evidence. We have selected the lamprey as a possible conscious organism and we first tested its fitness with the Integrative Neurobiological Model of Consciousness. Then, we tested the neurobiological and behavioural features of lamprey within differential criterion about animal consciousness, and finally we compared the neurobiological hallmarks of consciousness in humans with the characteristics of lamprey and the INMC. Our results suggest that the INMC presents a high fitness with many scientific criteria about consciousness, and that exist a high possibility of the presence of sensory consciousness in lamprey fishes. We conclude that consciousness can be explained through brain processes without the necessity of emergent properties or phenomenal entities, and despite more data is needed, the most parsimonious and ethical approach would be to consider at least all the vertebrates as possible conscious organisms.

Key words: *Consciousness, animal consciousness, Neurobiological Naturalism, Two-Stage Model, Neuronal Global Workspace, neurobiology of consciousness, consciousness criteria, lamprey nervous system, Qualia, Hard Problem.*

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1. INTRODUCTION

1.1. Motivation and Objectives

The problem of consciousness, or the so-called "mind-body problem", has been a subject of study mostly related for centuries with Philosophy, Theology, and the concept of soul (Crick & Koch, 1992). During the early 20th century, psychologists like William James started to focus his attention on it (James & Shook, 2011), but despite their implication, the concept itself has been conceived by many scientists to be too much philosophical and abstract to be studied through experimentation (Crick & Koch, 1992). Although, during the last decades, and probably thanks to the advances in brain sciences, we experienced an explosion of proposals concerning the problem of consciousness, both philosophical and neuroscientific approaches (Cavanna & Nani, 2014). Despite this recent scientific interest on consciousness, the actual knowledge about the real-time activity on the brain is limited. This handicap, combined with the ontological problem of experience (is unobservable), fertilized a field where neo-dualist theories are growing up with apparent scientific support, as well as the phylogenetic top-down approaches are centring the debate in humans.

Considering this state of the art, we identified a necessity to strengthen the scientific approach over the problem of consciousness. It is needed a defence inspired on the strict physicalism, and especially based on what neurobiology can explain about the topic. Thus, the main objectives of this work are set as follows:

Box 1. Establishment of the central objectives

1. Prove through evidence that consciousness is a **neurobiological process** that does not need to be conceived as an emergent property of matter.
2. Prove through evidence that consciousness is a neurobiological process present, at least, in **all the vertebrates.**

To do that, we present an own model of consciousness: The Integrative Neurobiological Model of Consciousness (INMC), conceived to integrate the cutting-edge neuroscientific and neurobiological theoretical frameworks in a single functional approach that allow us to answer the central questions: "*what is consciousness?*" and "*where can we find consciousness?*".

Through this work, the explanatory capacity of the INMC will be tested. Its *simplicity* (see Feuer, 1957*;* Friedman, 1974; Sober, 1975; Walsh, 1979; Thagard, 1988; Kitcher, 1989; Baker, 2003; Scorzato, 2012), *falsifiability* (see Popper, 1959) and its eliminatory nature (see Dennett, 1992) are three qualities that provides to the model the potential to offer a solid and a scientific solution to the philosophical topics on consciousness: the *Hard Problem* (Chalmers, 2010), the famous Nagel's *"what is like to be a bat?"* (Nagel, 1974) or the *Explanatory Gap* from Joseph Levine (1983). Moreover, INMC presents the potential to provide answers to other concerns about consciousness like its functionality in nature, its continuity in a single organism along with its life, or its computational replicability.

But the Integrative Neurobiological Model of Consciousness, and the objectives of this work, are the product of two recent theoretical frameworks: The Neurobiological Naturalism (NN) from Dr Todd E. Feinberg and Dr Jon M. Mallatt (see Feinberg & Mallatt, 2013; 2016a; 2016b; 2017; 2018; 2019), that sets a proposal on the neurobiological features of an organism to be conscious, and the Two-Stage Model (TSM) from Dr Michael H. Herzog and his colleagues, that sets important responses on the problem of perception continuity (Herzog et al., 2016), and offers a real-time perceptive mechanism based on the experimental evidence. The combining of these two scientific models results in an approach that highly fits with the *Neuronal Global Workspace* (NGW) of Stanislas Dehaene (Mashour et al.,2020), a proposal

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also based in the real-time processes of the brain. These three theoretical frameworks are the very foundations of the INMC. Although there exists an extended horizon of perspectives on the problem of consciousness that will interact with our work, our effort will be centred on the integration and defence of their proposals, as well as the interpretation of its implications.

1.2. Theoretical Framework
1.2.1. Neurobiological Naturalism

Todd E. Feinberg and Jon M. Mallatt are the first influential authors of this work. The extensive review of their thesis (Feinberg & Mallatt, 2013; 2016a; 2016b; 2017; 2018; 2019) provided us a rich and elegant neurobiological background with philosophical and phylogenetical perspectives. Their contributions to the state of the art are the following:

Box 2. Neurobiological Naturalism Thesis
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- The minimum requirement for **sensory consciousness** is a brain, including a forebrain, midbrain and hindbrain, with hierarchical systems of intercommunicating, isomorphically-organized processing nuclei that **extensively integrate** the different senses into representations, and a **widespread reticular formation** that integrates the sensory inputs and contributes to **attention, awareness and neural synchronization** (Feinberg & Mallatt, 2013). In resume, the organisms that translate sensory arrays into **mental images** possess *sensory consciousness* (Feinberg & Mallatt, 2013). This can only be observed in nervous systems with a spinal cord, a hindbrain with myelencephalon and metencephalon (including pons and cerebellum), midbrain with tegmentum and tectum, forebrain with diencephalon (including pretectum, thalamus, pineal gland, neurohypophysis, prethalamus and hypothalamus) and a telencephalon with cerebral hemispheres, as well as a greater limbic system, a reticular formation and autonomic nervous system (Feinberg & Mallatt, 2017).

- Consciousness is a **neurobiological process** that corresponds to certain animals with **special neurobiological features** (Feinberg & Mallatt, 2013; 2016a; 2016b; 2017; 2018; 2019). A group of characteristics that depends on the presence of previous evolutive traits and explain the specific conditions of the nature of consciousness. Thus, consciousness shares the features of all the living organisms; it is based on the cell as the key unit, is embodied, is a process which mechanisms and functions depend on the actions of the individual parts, it is restricted to a specific system in which the interactions between the parts are critical, and responds to a **hierarchy of different interacting levels** and progressive complexity (Feinberg & Mallatt, 2019). Then, the special neurobiological features are presented as (Feinberg & Mallatt, 2019):

  - *"**Neural complexity** (more than in a simple core brain)*
    - *Brain with many neurons (<100.000?)*
    - *Many subtypes of neurons*
  - ***Elaborated sensory organs***
    - *Eyes, touch receptors, taste, smell*
  - ***Neural hierarchies with neuron-neuron interactions***
    - *With reciprocal interaction in and between pathways for the different senses.*
    - *That generates computing modules, distributed but integrated.*
    - *With synchronized communication by brain-wave oscillations.*
    - *Where the high levels allow the complex processing and unity of consciousness.*
    - *With hierarchies that let consciousness predict events a fraction of a second in advance.*
  - ***Pathways that create mapped mental images or affective states***
    - *Neurons arranged in topographic maps of the outside world and body structures.*
    - *Valence coding of good and bad, for affective states.*
    - *Feed into pre-motor brain regions to motivate, choose and guide movements in space.*
  - ***Brain mechanisms for selective attention and arousal***
  - ***Memory, short-term or longer**"*

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- The appearance of **sensory consciousness in the animal kingdom** is coincident with the explosive radiation of animals in **the Cambrian Period.** Concretely, with the evolution of the distant senses, or the high-resolution eyes: a process completed by **520 mya** (Feinberg & Mallatt, 2017). Moreover, vision's neural pathways could have served as an organizational template for the expansion of other senses (Butler, 2000; Feinberg & Mallatt, 2017).

- Two big markers of consciousness in a phylogenetic level are the **optic tectum** and the **eyes.** The modern **lamprey** represents the oldest living vertebrate and is considered to be conscious since **it presents all the required neurobiological features.** This implies that **all the rest of vertebrates** matches the criteria for sensory consciousness (Feinberg & Mallatt, 2017), although they differentiate **tectum-based consciousness** from **cortex-based consciousness** (Feinberg & Mallatt, 2019). Moreover, some invertebrates match with the criteria of the special neurobiological features, despite they do not present the features in the same brain areas: some arthropods and cephalopods are candidates to be sensory conscious (Feinberg & Mallatt, 2019).

- Sensory consciousness can be divided into three partially overlapping domains: exteroceptive, affective and interoceptive. The **exteroceptive domain** is constructed through sensory maps, the **affective domain** is constructed through internal valences, and the **interoceptive domain** is an in-between domain that includes both mapped sensory representations of the body's organs and the affective information that protect the somatic functions (Feinberg & Mallatt, 2019).

Todd E. Feinberg and Jon M. Mallatt remarks de diversity of causes and mechanisms behind sensory consciousness: their thesis is a proposal that charges against the approach of many actual theories that are trying to reduce consciousness to single features or few components: fundamental forces, quantum microtubules, a global workspace, integrated information, cognitive and computational capacities, reciprocal and oscillatory neuronal communications, attentional aspects, new complex physics, predictive properties or contextual emergence in systems theory (Feinberg & Mallatt, 2019). All those theories are establishing the problem in a few causes. The value of the proposal of the Neurobiological Naturalism is specifically the consideration of the biological and neurobiological complexity by which consciousness can be explained (Feinberg & Mallatt, 2013; 2016a; 2016b; 2017; 2018; 2019). They encourage and puts in evidence the necessity of integrative theories to approach the problem (Feinberg & Mallatt, 2019).

Finally, on their first paper from 2013, they propose a way to test their thesis: the finding of re-entrant and recurrent processing on the thalamo-tectal pathways in fishes could mean that whenever sensory information reaches a successive level in a hierarchy, the higher level sends signals back to the lower levels, as it has been demonstrated occurs in the mammalian brain of higher primates (Feinberg & Mallatt, 2013).

1.2.2. Two-Stage Model

According to the Two-Stage Model of perception, the sensory inputs are first unconsciously analyzed in a period of at least 400 ms during that the information is processed and classified in a coherent structure of signals, to afterwards broadcast the refined data into a widespread system that receives and encodes the final perception. The Two-Stage Model resolves the paradigm of the time window over perception, where two opposed schools argued over the years if the perception is continuous or discrete through the time (Herzong et al., 2016). Their proposal establishes:

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Box 3. Two-Stage Model Proposal
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- Sensory stimuli are encoded with **quasi-continuous resolution:** this is, from 1ms to hundreds of milliseconds.
- Sensory information **remains unperceived at least during 400 ms.** This is the time that the brain uses to integrate, coordinate, signify and codify the global entrance of data.
- During an unknown period (<400ms) the **brain generates a global map of successes** through the integrated and re-encoded data.

This implies that the brain does not perceive continuously from the crude sensory data of the environment and itself, but it has structures that allow the codification of integrated results, to interpret the merged information in inferior times and lesser neurons. The Two-Stage Model proposes that the perception of time it is not the perception of a real-time continuous entrance, but a specific neural code that resumes and encodes for periods of time (Herzong et al., 2016). The implications of this approach seem crucial to understanding the building blocks of the organismic subjective perception or sensory consciousness: the world is perceived in snapshots, but snapshots that include all the crucial and quasi-continuous data of the last moment; the duration of the stimuli, its order, its significance, salience, etc. (Herzong et al., 2016). Through this model, all the paradigmatic perceptive experiments and the dilemma of continuity vs discrete percepts are elegantly resolved (Herzong et al., 2016).

1.2.3. Neuronal Global Workspace

The thesis of Stanislas Dehaene proposes the existence of a widespread but defined neuronal network with localized, specialized and modular cortical areas that process perceptions, as well as motor responses, memory and evaluative information with widely distributed excitatory neurons with long-range connectivity that forms reciprocally connected tracts with the capacity of ensuring or suppress the contribution of specific neural processors (Mashour et al.,2020). This distributed reticular formation of neurons is conceived with the ability to receive bottom-up information and transmit top-down results to the different processors. Therefore, its role consist of receiving and broadcasting information (Mashour et al.,2020). The Neuronal Global Workspace also introduces a concept called *ignition* (Mashour et al.,2020) that the Two-Stage Model named *attractor state* (Herzong et al., 2016). This is, ignition is the sudden, coherent and exclusive activation of subsets of neurons inside the global workspace that codes for the current conscious content (Mashour et al.,2020). The rest of the neurons of the NGW are inhibited during the ignition, and the event can be provoked by external stimuli or can be triggered by spontaneous and stochastic activity (Mashour et al.,2020).

The specific form of the NGW is conceived as a distributed net of neurons through many brain regions with the capacity to amplify, sustain and send the information to specialized thalamocortical loops, with a special contribution of the prefrontal cortex in humans, but not restricted to it (Mashour et al.,2020). The NGW proposed five different components being integrated in the global workspace (Mashour et al.,2020) (see Box 5).

The different variables and features of the three models allowed us to develop the INMC with a combination of the highly explanatory characteristics exposed. The process of selection is explained in the section 3.

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Box 4. Neuronal Global Workspace Main Components
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- **Evaluative Systems** (Value)
- **Attentional Systems** (Focusing)
- **Long-Term Memory** (Past)
- **Motor Systems** (Future)
- **Perceptual Systems** (Present)
- **Neuronal Global Workspace**

2. METHOD

This work has been realized through a conjunct of methodical steps. The first step has been the development of the *Integrative Neurobiological Model of Consciousness* (see Appendix 1) based on the Neurobiological Naturalism, the Two-Stage Model and the Neuronal Global Workspace. The common and remarkable features of the three approaches have been merged, characterized and operationalized to be concreted and mutually related. The second stage has consisted in the establishment of the working hypothesis based on the objectives of this work:

Box 5. Working hypothesis of the Integrative Neurobiological Model of Consciousness
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- **Null Hypothesis:** Consciousness is an emergent property
- **First Hypothesis:** Consciousness is a process that brain does
- **Second Hypothesis:** Consciousness is at least a vertebrate function

The subsequent step has been the design of a method to put under test the hypothesis. First, we selected the lampreys as an animal model to compare the INMC with an organism that according to the Neurobiological Naturalism, could be conscious. Once the fitness between the animal model and the INMC have been tested, we searched for differential criteria: this is, criteria that authors without relation with our referential theoretical frameworks proposed to consider the existence of consciousness in animals. The third and last test has been the crossed comparison between the INMC, the lamprey brain and the considered crucial features for consciousness in humans. This allowed us to test at the same time the validity of the model and the possible presence of consciousness in lampreys, first ensuring its mutual fitness, second testing the bounded model with alternative criteria, and finally testing the model with criteria applied on clearly conscious organisms.

The evidence research has been realized within a qualitative systematic review using the following databases: NCBI and PubMed, ResearchGate, PsycInfo, Scopus, and scientific editorials and journals: Elsevier, Frontiers in Psychology, MIT Press, Scientific American, Nature and Science. The main searching words have been: *Consciousness; origin of consciousness; animal consciousness; primary consciousness; minimal consciousness; neural topographic maps; neural sensory maps; neural basis of consciousness; nervous system evolution; lamprey nervous system; neural networks.* Every paper or book in the neuroscientific field has been extracted from the previous enlisted research portals without exception, thus ensuring the compliance of ethical and legal requirements inherent to the publication standards. In the field of philosophy of mind, all the papers consulted have been extracted from the database PhilPapers

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or from the UAB library's catalogue, also ensuring the compliance of ethical and legal requirements from European and American standards of publication. Finally, the selection conditions for the referenced papers have been: (1) English as the only language admitted (2) at least 80% of the references must be from 2009 to actuality when related to the field of neuroscience and (3) the observational data must have been extracted from papers unrelated with the work of Todd E. Feinberg & Jon M. Mallatt.

3. INTEGRATIVE NEUROBIOLOGICAL MODEL OF CONSCIOUSNESS
3.1. Variable extraction from the referential models

The development of the INMC (see Appendix 1) starts with the selection of the relevant variables from the influential models. This exercise is done with a cross-comparison of trunk variables between the three referential approaches of our work. Figure 1 illustrates the process of the relation between the variables, where it can be observed that every final variable of the INMC appears at least in two different approaches. The extracted variables have been: (1) Perception Coding Structures with the capacity of predictive processing, (2) Timeframes, (3) Topographic sensory structures with single-sense integration and (4) Multisensory Integration Structures, as well as (5) Valence Coding, (6) Salience Coding, (7) Memory and (8) Pre-motor Structures. Finally: (9) Neural Synchronization. We divided the sensory structures into single-sense integration architectures and multisensory architectures to differentiate between processes that can take place in single structures, from higher processes that need to be involved in long-range activity between different areas.

Figure 1. Variable relationship between referential theoretical frameworks and the INMC
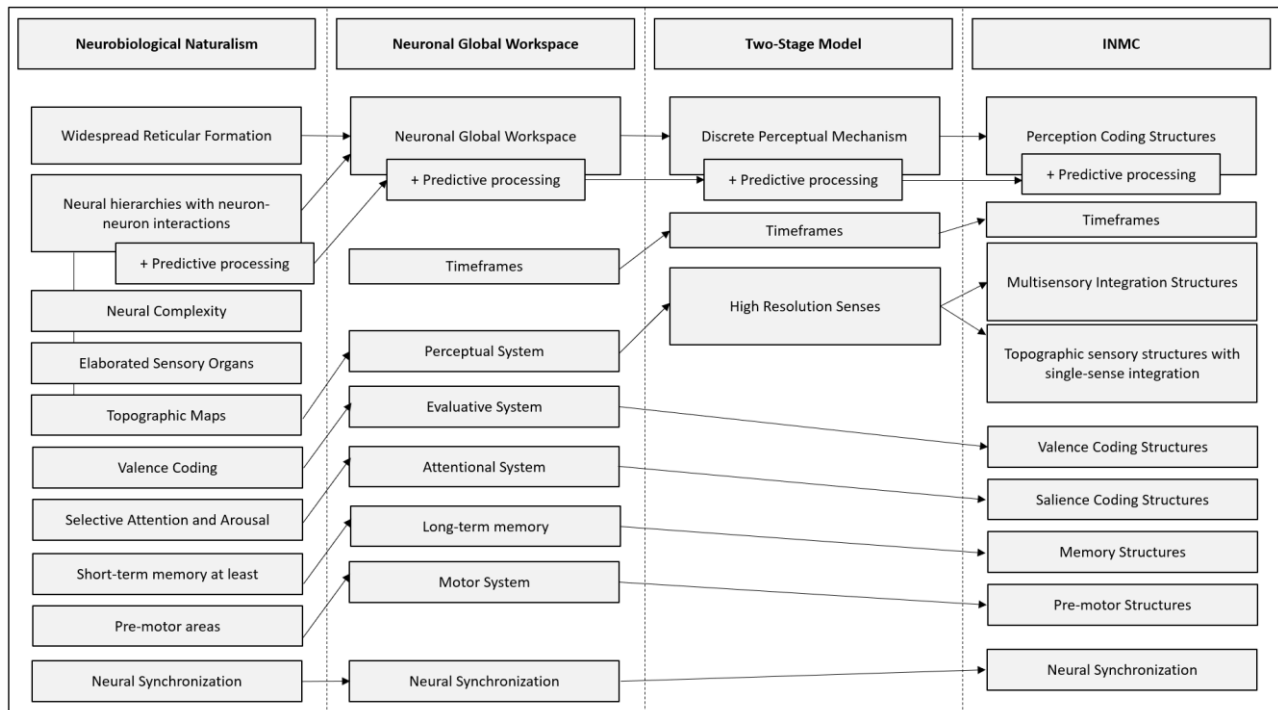
Designed through a review on the Neurobiological Naturalism (Feinberg & Mallatt, 2013; 2016a; 2016b; 2017; 2018; 2019), the Neuronal Global Workspace (Mashour et al.,2020) and the Two-Stage Model (Herzong et al., 2016).

3.2. INMC axioms

Although the extracted variables are highly explicative, the principal objective of this model is to offer a first explanation of how consciousness can be conceived simply as a process. To reach this, we developed

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a list of foundational axioms of the model that helped us to interpret the interaction between the variables, as well as set some strong precepts in which build our conclusions, crucially related with the evolution of the nervous system.

Box 6. Foundational Axioms of the Integrative Neurobiological Model of Consciousness
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- **A1. Neurons are stimuli-response organisms.**
    - **A1.1** A stimuli for a neuron is any physical or chemical change on its close environment that produces organismic responses.
    - **A1.2** The effects of the cellular response of one or multiple neurons can be interpreted as stimuli by other neurons.
    - **A1.3** Neurons can establish nets in which each cell is physically related to others through synapsis.
    - **A1.4** Synapsis are specialized structures in which neurons can physically determine consecutive stimuli-response relationships over time, thus increasing its correlational activity.
    - **A1.5** The physically determined synapsis allows a specific spatiotemporal correspondence between neurons, as well as its isolation from others, thus specific nets become specialized.
    - **A1.6** The capacity of the neurons to generate specialized nets incorporated new functionalities to the bodies of their organisms.
    - **A1.7** New nervous functionalities carried new opportunities to increase organismic fitness over competitors.
    - **A1.8** The specialized functionalities evolved through the nervous system evolution.
- **A2.** The early evolution of the nervous system is characterized by **the expansion of the number of neurons** between receptors and the resultant motor response of the organism.
- **A3.** The evolution of the nervous system is characterized by the acquisition of **new nervous functionalities.**
- **A4.** The evolution of the nervous system promoted the **acquisition of new specialized sensory receptors** and organs.
- **A5.** Organisms with the functionality of **integrating sensory processed information** from different receptors **increased its fitness.**
- **A6. Sensory consciousness appears** in some moment of the evolution of the sensory functionalities of the nervous system.

The axioms reveal the necessity to put the attention on the minimal component of the brain: the neurons, and build all the boundaries between variables through this unit. Moreover, we identify the necessity to differentiate the structural variables (this is, what a nervous system needs to reach consciousness) from the process variables: the activity of these structures in real-time. A nervous system cannot be conscious without specific and diverse structural components, but even with these architectures, consciousness is not defined. It is needed a process through the structures during specific timeframes. Without patterns of neural activity, consciousness cannot exist, and without specialized and trunk structures, the patterns of neural activity cannot be considered conscious experience. Thus, the INMC integrates all the variables of its theoretical framework through our own proposal on the neural activity patterns.

3.3. INMC final components

The final components of the INMC have been mathematically characterized to facilitate its mutual relationship. Our interest resided to generate a template of mathematical relations that allow us to present consciousness as a process, thus supporting the logical and scientific reasoning. Since our mathematical knowledge is deficient, the operationalization has been carried using undefined functions and conjuncts: this implies that we are not proposing the formula of consciousness, but a castle of interactions, too much intricated by the moment to be specified, but with a structure and identified components. Every conjunct and every unspecified function represent a field of knowledge unknown by us, but we hope the global structure is sufficiently determined to promote new computational, mathematical and bioscientific thinking over this field.

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The final components have been: (1) Structural variables, (2) Time Window, (3) Externally Triggered Processes, (4) Internally Triggered Processes, (5) Spatiotemporal Synchronization, (6) Perceptive Patterns.

Box 7. Structural Variables of the INMC
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Includes all the architectural variables: this is, how a brain capable to be conscious is organized. **Its minimal unit is the neuron** ($u_i (x, y, z)$) that takes a specific position in the **tridimensional space**. The physical, chemical and electrical relationship between neurons is established by **a function that represents the synapsis:**

$$s_n = s(u_{i1}(x, y, z), u_{i2}(x, y, z))$$

Every functional module of **interrelated neurons** (ω_k) is represented by a function that puts in relation different synapsed neurons (s_n):

$$\omega_k = h(s_1, s_2 \dots s_n)$$

And different functional modules establish bigger modules with **combined capacities**. For example:

$$\omega_4 = \omega(\omega_1, \omega_2, \omega_3)$$

In addition, **a brain capable to be conscious** needs to be composed by interrelated big neural networks with topographic single sense integration (Top), multisensory integration (Int), valence coding (Val), salience coding (Sal), memory (Mem), and perception (with predictive capacities) structures (Per):

$$Top = f(\omega_i \dots \omega_l)$$
$$Int = f(\omega_r \dots \omega_s)$$
$$Val, Sal, Mem = f(\omega_m \dots \omega_n)$$
$$Per = f(\omega_j \dots \omega_k)$$

The whole conjunct of this networks constitutes the structures of a brain with the capacity to be conscious:

$$\Pi = \{\omega_1, \omega_2 \dots \omega_k\} = \{Top, Int, Vl, Sl, Ln, Per\}$$

Note that by the time the pre-motor structures have been neglected because of a lack of data about its specific contribution in the generation of the conscious experience, instead of its nature of content of the conscious experience itself.

Box 8. Time Window
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The Time Window of conscious experience includes two moments: Δt_α and Δt_β

Δt_α is conceived to be the lapse of time where **all the structure processes the whole inputs**, and Δt_β is conceived to be the lapse of time where all the processed inputs are **broadcasted to the perception structures**. Each lapse of time can be thought as a conjunct of minor timeframes:

$$\Delta t_\alpha = \{\Delta t_{mn}\} = \{\Delta t_{m1}, \Delta t_{m2}, \Delta t_{m3}, \dots\}$$
$$\Delta t_m = \{\Delta t_{wn}\} = \{\Delta t_{w1}, \Delta t_{w2}, \Delta t_{w3}, \dots\}$$

Where $\Delta t_\alpha > 400ms$
Where $\Delta t_m < 400ms$
Where $\Delta t_w < \Delta t_m < \Delta t_\alpha$

Also:

$$\Delta t_\beta = \{\Delta t_{bn}\} = \{\Delta t_{b1}, \Delta t_{b2,} \Delta t_{b3}, \dots\}$$
$$\text{Where } \Delta t_\beta < 400ms \text{ and } \Delta t_\alpha \neq \Delta t_\beta$$

Box 9. Externally Triggered Processes

The Externally Triggered Processes, or $E(\Delta t_\alpha)$, are the resultant set of neural electrochemical activity provoked by stimuli from the external senses (body or environment) interacting in a **cascade of stimuli-response activity between neurons**. Its shape depends on the initial input and the characteristics of the neural architecture attached to the input entrance:

$$E(\Delta t_\alpha) = \{e_i\} = \{e_1, e_2, e_3, \dots\}$$
$$\text{Where } e_i(\Delta t_{mn}) = e(res_i, \omega_i)$$
$$\text{Where } res_i = res(inp_i(\Delta t_{wn}), u_i(x,y,z))$$

Where res_i is the response event of a neuron with the potential to activate a cascade of responses in a specific neural network, and e_i the resulting pattern of stimuli-responses through a specific ω_i.

Box 10. Internally Triggered Processes

The Internally Triggered Processes $I(\Delta t_\alpha)$ can be originated in a previous moment by past stimuli-response patterns or can be also interpreted as the effect of cell clocks or chemical dynamics, including the effects of the glia, the maintenance of neurotransmitter in the synaptic space, etc. Therefore, **includes all the causes of activity unrelated with the external receptors** in the Δt_α moment:

$$I(\Delta t_\alpha) = \{v_i\} = \{v_1, v_2, v_3, \dots\}$$
$$\text{Where } v_i(\Delta t_{mn}) = v(inn_i, \omega_i)$$
$$\text{Where } inn_i = inn(inp_i(\Delta t_{wn})), u_i(x,y,z))$$

Where inn_i represents the inner or internally elicited activity of a neuron with the potential to activate a neural network.

Box 11. Spatiotemporal Synchronization

While this model **cannot explain how every neural network must behave** to generate significant data, it is necessary to include a restrictive variable. Without the accomplishment of the Γ condition, the presence of $E(\Delta t_\alpha)$, $I(\Delta t_\alpha)$ and Π cannot explain the conscious perception. Within this restriction **we impose to the model** that the patterns generated will be sufficiently significant, ordered and coherent to trigger perceptions.

Box 12. Perceptive Patterns

The Perceptive Patterns K during Δt_β **will be the result** of the spatiotemporally synchronized (Γ) previous Internally and Externally Triggered Processes, $I(\Delta t_\alpha)$ and $E(\Delta t_\alpha)$, through a structure Π. Specifically, the Perceptive Patterns will be found in the Perceptive Structures and its extensions along the whole system:

$$K(\Delta t_\beta) = K(E(\Delta t_\alpha), I(\Delta t_\alpha), \Pi) \cdot \Gamma = \{k_n\} = \{k_1, k_2, k_3, \dots\}$$
$$\text{Where } k_n(\Delta t_{bn}) = k(e_i(\Delta t_{mn}), v_i(\Delta t_{mn}), \omega_j) \cdot \Gamma$$

Figure 2 and Figure 3 illustrates in an abstract way the two moments of the conscious perception of an organism through all the components of the INMC. The black and white graphic represents the structure of the brain with specialized neural networks, and the coloured relations represents the processes that take place alongside these structures. In every moment of the Time Window, all that is happening is a process: the brain does not reach a specific state of consciousness through these processes, but consciousness is the processes itself.

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Figure 2. Abstract example of the processes previous to perception through the INMC
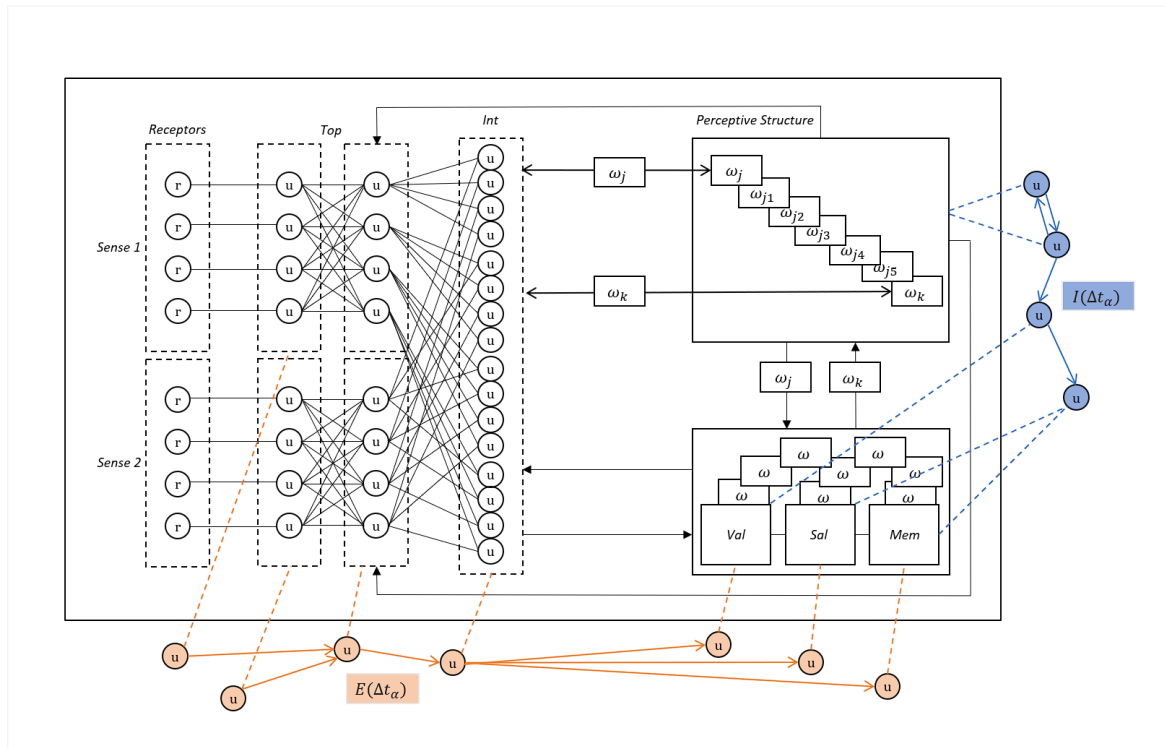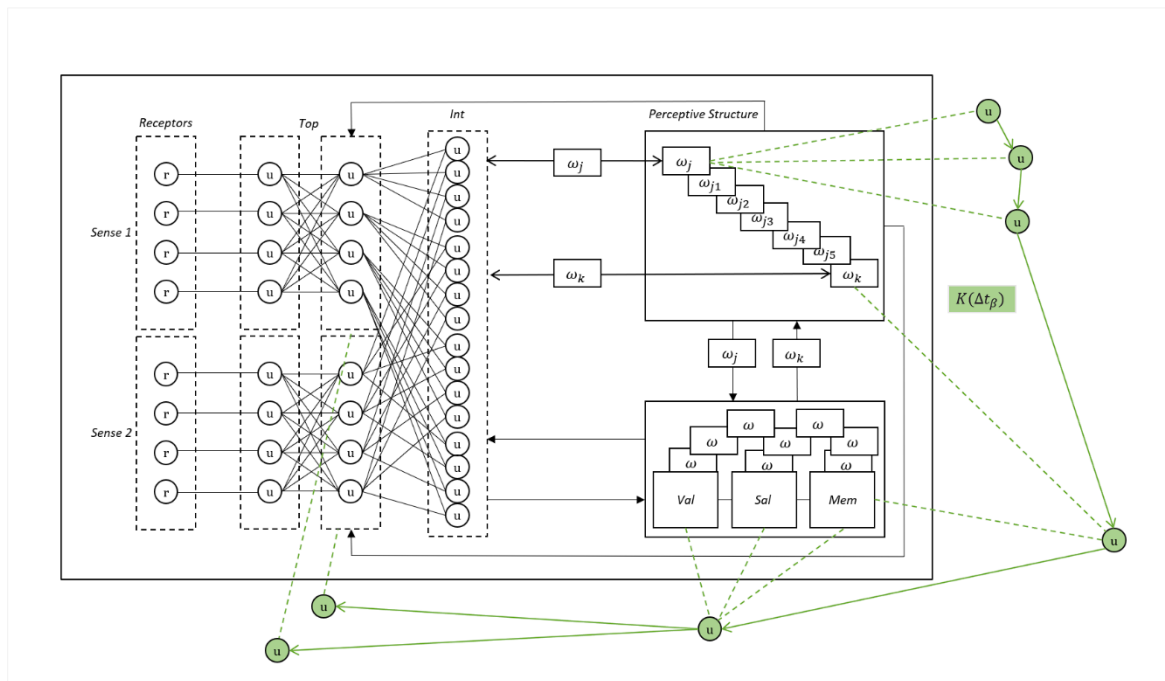

Figure 3. Abstract example of the resulting process of perception through the INMC

With the model introduced and the method explained, we present the results of the work.

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4. RESEARCH AND RESULTS
4.1. Fitness of the INMC in lamprey fishes
4.1.1. Topographic single sense integration and multisensory integration

An elegant study from 2015 revealed the crucial role of the cranial neural crest cells (cNCCs) on the establishment of sequential order between peripheral sensory neurons and neural tube border cells in zebrafish embryo; a relation that sets the isomorphic structure of the sensory system (Zecca et al., 2015). This is, the presence of neural crest and placodes during the embryo development of an organism is a sign of its later sensory topographic structure.

In parallel, another study has been carried out with sea lampreys in an embryonic stage using gene expression ablation (CRISPR/Cas9 gene-editing) of *SoxE2* and *FoxD-A* that encodes the homonymous neural crest transcription factors. The mutant groups of lamprey *SoxE2* and *FoxD-A* revealed neural patterning defects on HuC/D-positive sensory neurons, being misplaced or dissociated of their corresponding ganglia (Yuan et al., 2020). Their results suggest that cNCCs are not required for cranial ganglia cell specification but for shaping the morphology of the sensory systems during the embryo development (Yuan et al., 2020). Hence, considering that lamprey presents neural crest and placodes, we can accept it as a carrier of isomorphic maps. Moreover, other evidence indicates that the medial pallium of ancestral fishes became specialized to generate navigation allocentric maps (Rodríguez et al., 2002), as well as the optic tectum of the lamprey receives data from the visual system and electrosensory inputs from the lateral line system (Suzuki & Grillner, 2018).

4.1.2. Valence, salience, memory and perception coding structures

Despite lampreys do not present amygdala, its brain explains a lot about the evolution of the limbic system. The ventral and lateral pallium of the first vertebrates evolved in later vertebrates to be the superficial and deep amygdalar nuclei, as well as the entire striatum and pallidum of the jawless fishes gave rise to the extended amygdalar complex in their vertebrate successors (Loonen & Ivanova, 2016). The amygdalar complex is known to be relevant for allowing the organism to select and attend sensory stimuli crucial to trigger reward-seeking and misery-fleeing behaviours in vertebrates (Loonen & Ivanova, 2016). But have the lamprey these capacities without a differentiated amygdala? The answer seems to be affirmative. Lamprey present aversive and appetitive stimuli-related behaviour (Pietrzakowski et al., 2013; Imre et al., 2016) as well as crucial structures to salient stimuli coding: its optic tectum operates on its own to develop gaze reorientation commands through multisensory stimuli computation (Kardamarkis et al., 2016), and there are crucial hallmarks of attention-related pathways in lamprey's tectum, like direct dopaminergic projections that encode specifically for saliency (Pérez-Fernández et al., 2017).

In addition, the modern jawless fishes present a small but well-developed dorsal thalamus which connects the tectum with the optic tract and the caudal parts of the pallium (Loonen & Ivanova, 2016), this last one related to the hippocampal primordium and subhippocampal lobe (Loonen & Ivanova, 2016), areas linked to spatial memory (Rodríguez et al., 2002). Last but not least, the three-layered structure of the mammalian cortex, historically conceived to be based in the reptilian cortex has been found in the lateral pallium of the lamprey, with GABAergic interneurons, glutamatergic cells and projections similar to the mammal brain (Suryanarayana et al., 2017): a lamprey area that is known to produce and mediate goal-directed behaviours and highly interconnected with the thalamus (Suryanarayana et al., 2017). Moreover, the high interconnectivity between areas in lamprey has been reported recently by experts on the field. Concretely, we can find reciprocal signalling between the optic tectum, the pretectum, the thalamus, the pallium and the basal ganglia of the lamprey fishes (Suzuki & Grillner, 2018).

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4.1.3. Neural spatiotemporal synchronization

A recent study demonstrated the existence of previously theoretically hypothesized inhibitory circuits in the modern lamprey that allows the coherent integration of the high amount of different environmental stimuli (Kardamakis et al., 2016). According to the study, the tectal GABAergic system of the lamprey fishes that regulates the excitatory visual and electrosensory input integration is provided by a net of short and long-range inhibitory connections across the optic tectum (Kardamakis et al., 2016). These neural pathways allow constantly recruited inhibition triggered by the two types of the sensory stimulus (that are exciting the GABAergic system at the same time); a process that reset continuously the active areas of the system to enable the entrance and codification of new set of stimuli (Kardamakis et al., 2016), thus generating a constant flow of information (Kardamakis et al., 2016). Remarkably, the study also evidence that the optic tectum of the lamprey fishes is spatiotopic organized in columns with output neurons receiving retinal excitation from the same quadrant (Kardamakis et al., 2016).

This presented inhibitory system is similar to the system proposed by the NGW model during the ignitions. Moreover, this is only an example through which spatiotemporal synchronization of the neural networks can be inferred.

4.2. Testing lamprey sensory consciousness through differential criteria

To carry out with the comparison we have collected different criteria across scientific disciplines and authors. We have extracted 11 variables from the scientific literature consulted (within a research based on the words *"(Consciousness)"* AND *"criteria"* and *"(Consciousness)"* AND *"animal"*), which has been based only on neuroscientific studies or reviews. Some variables have been merged because of its similar explanatory potential; coincident or similar criteria between studies are reflected in the *'References'* column of Table 1.

The variety between criteria has been ensured by the inclusion of variables from different fields related with neuroscience: Clinical criteria in humans with MCS (Coleman et al., 2002); Cognitive sciences (O'regan, 2005); Cephalopod studies (Mather, 2007); Predictive coding studies (Hohwy, 2012; Panichello et al., 2013; Seth et al., 2012; Strauss et al., 2015); a European Food Safety Authority report (Neindre et al., 2017) and other relevant studies based on non-human consciousness (Pennartz et al., 2019). Some variables have been found redundant with our model, and the rest of them have shown the following fitness:

- **Var 1. Anticipatory behaviour.** Describes the capacity of an animal to predict events in the future. The trait can be traced from insects to primates and humans, considering the neurobiological presence of internal timing mechanisms that allow the animal fitness in a "timescale from seconds to seasons" (Krebs et al., 2017). It is directly related to attentional mechanisms, operant conditioning, zeitgebers and stimuli processing.

- **Var 2. Predictive coding & Top-Down processing.** Describes the presence of neural top-down pathways, in the opposite direction of the sensory entrance pathways, with the capacity to generate predictive models of the environment and reduce the requirements of the sensory processors, which adopts a role of error informers. The brain includes pathways that generate expectations from the previous sensory input, and compare this top-down expectation with the actual sensory input. This results in a cascade of constant and simultaneous predictions and error corrections that tends to an error minimization (Hohwy, 2012). Thus the final source of the sensory experience is not the bottom-up entrance signals but the top-down processing through previous sensory information (Hohwy, 2012; Panichello et al., 2013; Seth et al., 2012; Strauss et al., 2015).

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The prediction generator process needs the integration of different sensory stimuli to build environmental hypothesis (maps, images) and provide a model to explain the attentional responses of an organism (see Hohwy, 2012). This can be reached only across a generative system with strong representative power of the physical and chemical environment of the individual.

In lampreys, we cannot find direct evidence of perceptive processing, but we can find pathways compatible with the idea. Concretely, the pallium of the lamprey, which has been found to be three-layered on its medial zone, send efferences directly to the optic tectum and the pretectum, the first sensory entrances on the visual system of the animal. The pallium also maintains reciprocal connectivity with the thalamus, that is reciprocally connected with the optic tectum at the same time (Suzuki & Grillner, 2018).

- **Var 3. Visuospatial behaviour.** Despite there is no explicit evidence of consciousness directly related with the navigation behaviour of an organism using visual data (Pennartz et al., 2019), the behaviour of an animal, highly correlated with its environmental cues (collected through distant sensors) can be an indicator of the existence of situational perceptive maps (Pennartz et al., 2019). Moreover, the behaviour based on the concept of object permanence becomes strong evidence of perceptual images and representations from the organism (Pennartz et al., 2019). This is used by Pennartz as criteria for defending the existence of sensory consciousness at least in mammals and birds (Pennartz et al., 2019). In parallel, recently has been demonstrated the object permanence behaviour in four species of fishes (Sovrano et al., 2018). Again, there is a lack of evidence related directly with lamprey, but the presence of this trait in other fishes is remarkable. The visuospatial behaviour is used in clinical studies to infer Minimally Conscious State in patients with Disorders of Consciousness (Coleman et al., 2002).
Another criterion used by Pennartz to infer consciousness is the presence of illusions and multistable perceptions, that indicates an active role of the brain in constructing models of the environment instead of reacting to simple stimuli entrances (Pennartz et al., 2019). Remarkably, this trait has also been recently proven in zebrafish and guppy (Gori et al., 2014), indicating that it is not a cortex-based characteristic.

- **Var 4. Communicating system.** In clinical studies, the capacity to minimally communicate is considered a criterion to infer MCS in a patient with DoC (Coleman et al., 2002). In the field of non-human animal consciousness, the capacity of communicating has been considered as a feature of conscious organisms, and concretely, has been considered a feature that supports the attribution of consciousness in cephalopods (Mather, 2007). This allows us to consider communication as a simple interchange of information between organisms. In that way, the lamprey shows a high conspecific chemical interaction that is conserved across vertebrate taxonomy; the pheromonal communication system (Buchinger et al., 2019). The olfactory bulb in lamprey is chemotopic organized and responds to pheromonal stimuli through sensory olfactory neurons: this is, its communicating system is supported by perceptual odorant maps (Green et al., 2017).

- **Var 5. Metacognitive performance.** Despite historically being considered a human capacity, during the last years, metacognition has been studied in mammals and birds as the capacity of the individual to be aware of its own uncertainty (Neindre et al., 2017; Pennartz et al., 2019). Under this specific definition, metacognition has been found even in honeybees (*Apis mellifera*) (Perry & Barron, 2013), that shown avoiding behaviours in a reward/punishment task when they lack the information to solve

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the problem (Perry & Barron, 2013). Again, there is a lack of studies in lamprey, although the presence of the trait in honeybees suggests its extension in the animal kingdom.

- **Var 6. Sleep/wake activity.** This criterion is shared between human clinical studies (Coleman et al., 2002), mammals and bird studies (Neindre et al., 2017) and non-vertebrate studies (Mather, 2007). The sleeping capacity of an organism allows us to specify moments in which probably is unconscious, and moments in which probably it is conscious. Despite we think this can be a tricky hallmark, lamprey presents circadian locomotor rhythms with long periods of minimal locomotor activity (Zvezdin et al., 2019) and a specific brain structure, the cerebellar rhombic lip, highly conserved across species, including humans, and related with it. Despite we have not found studies about the possibility of REM and NREM phases in lamprey, the behavioural criteria used in non-vertebrate consciousness studies matches with the provided data.

Table 1. Differential observable criteria to infer consciousness in human and non-human animals

	Variable	Variable type	Fitness	References
(1)	Expectations / Anticipatory behaviour	BH	+ (Inferred)	Neindre et al., 2017
(2)	Rostral-to-caudal processing after caudal-to-rostral sensory pathways / Predictive coding with top-down computations	NB	+ (Inferred)	Neindre et al., 2017 Strauss et al., 2015 Seth et al., 2012 Panichello et al., 2013 Hohwy, 2012
(3)	Visuospatial behaviour / Illusion and multistable perception	BH	+ (Inferred)	Pennartz et al., 2019 Coleman et al., 2002
(4)	Communicating system	BH	+	Mather, 2007 Coleman et al., 2002
(5)	Metacognitive performance	BH	+ (Inferred)	Pennartz et al., 2019 Neindre et al., 2017
(6)	Sleep/wake activity	BH / NB	+	Neindre et al., 2017 Mather, 2007 Coleman et al., 2002
(7)	Thalamocortical system or functional analogues / Central control and global workspace	NB	Redundant	Pennartz et al., 2019 Neindre et al., 2017 Mather, 2007
(8)	Corporality / Self-location in space	BH / NB	Redundant	Mather, 2007 O'regan et al., 2005 Coleman et al., 2002
(9)	Goal-directed behaviour with Arousal and Pleasure/Displeasure responses	BH / NB	Redundant	Pennartz et al., 2019 Neindre et al., 2017 Coleman et al., 2002

(10)	Alerting capacity	BH	Redundant	Neindre et al., 2017 O'regan et al., 2005
(11)	Memory and Learning	BH / NB	Redundant	Pennartz et al., 2019 Neindre et al., 2017 Mather, 2007

BH: Behavioural; NB: Neurobiological; Fitness: Potential of our vertebrate model to sustain the presented variables

4.3. Testing INMC and lamprey fitness with human consciousness criteria

The final test provided us with 10 variables considered indispensable features for consciousness in humans. As it is presented in Table 2, it is possible to propose homologous characteristics with similar functionalities in lamprey, despite this is an inferential exercise. More data in both directions is needed to prove the similarities between brains. By the time, all that can be ensured is the considerable possibility of lamprey to present consciousness.

Table 2. Crucial features for consciousness in humans and homologous features in lamprey

	Indispensable human brain feature	Variable	Lamprey homologous	References
(1)	High-order associative areas	Per, Int	Three-layered lateral pallium	[h] Laureys, 2005 [v] Suryanarayana et al., 2017
(2)	Long-range synchronization	Γ	Long-range synchronization	[h] Wenzel et al., 2018 [v] Massarelli et al., 2016
(3)	Positive and negative default mode network (DMN)	Π	Interconnected thalamus and pallium, telencephalon	[h] Perri et al., 2016 [v] Suryanarayana et al., 2017
(4)	Dorsal attention network (DAT) and temporal connections to DMN	Π	Midbrain, optic tectum, pallium	[h] Huang et al., 2020 [v] Robertson et al., 2006
(5)	Top-Down sensory modulation pathways	Per	Top-Down sensory modulation pathways	[h] Sikkens et al., 2019 [v] Sovrano et al., 2018
(6)	Functional connectivity patterns	K, Per	Interconnected OT, PT, TH, PA, BG	[h] Lee et al., 2017 [v] Suzuki & Grillner, 2018
(7)	Reticular Activating System	Π	Hindbrain, midbrain	[h] Garcia-Rill et al., 2013 [v] Wannier et al., 1998 *
(8)	Thalamocortical circuits	Per, Int	Interconnected thalamus and pallium	[h] Redinbaugh et al., 2020 [v] Suryanarayana et al., 2017
(9)	Posterior cingulate cortex and precuneus	Per, Int	Telencephalon	[h] Vogt & Laureys, 2005 [v] Suryanarayana et al., 2017
(10)	Habenula	Int, Val	Habenula	[h] Gelegen et al., 2018 [v] Yáñez & Anadon, 1994

[h] human data. [v] lamprey/other fishes data. OT: optic tectum; PT: Pretectum; TH: thalamus; PA: Pallium; BG: Basal ganglia.
(*) Also see Fernández-López et al., 2017.

5.   DISCUSSION
5.1.   Hypothesis refutation
5.1.1.   Null Hypothesis: Consciousness is an emergent property

Thanks to the structure of the INCM, that entails the proposal of three scientific theoretical frameworks related with consciousness, the resulting mathematical expression, and the results of our research, we can sustain that *consciousness* is the **verbal construct** that represents $K(\Delta t_\beta) = K(E(\Delta t_\alpha), I(\Delta t_\alpha), \Pi) \cdot \Gamma$. Considering consciousness as an emergent property of the brain's processes would imply strange relationships like the following:

$$\Phi = \Phi\big(K(\Delta t_\beta), E(\Delta t_\alpha), I(\Delta t_\alpha), \Pi\big) \cdot \Gamma$$

And although it can be conceived, it implies the entrance of unknown variables to the formula. In this example, Φ is an abstract and uncertain component: the emergent result of a process. To resolve its vague definition, some authors are invoking new physical properties and proposing new forms of dualism (Feinberg & Mallatt, 2019). As it happened with the verbal construct of "life", that it can be reduced to a conjunct of specific chemical processes, we defend that consciousness does not need more than conjuncts of specific biological processes to be explained:

$$K(\Delta t_\beta) = K(E(\Delta t_\alpha), I(\Delta t_\alpha), \Pi) \cdot \Gamma$$

While we cannot refute the possibility of consciousness as an emergent property, we find that our model is endowed with some valuable characteristics that by the moment, the emergentist proposals does not have. This is, our model is **simpler:** described through the 3+1 dimensions, raised in the actual physical, chemical and biological knowledge; and is **falsifiable:** every component of the model can be put under test.

5.1.2.   First Hypothesis: Consciousness is a process that brain does

Thus, we first conclude that, considering the actual evidence, the most parsimonious approach is to accept consciousness as a process until proven otherwise. Being scientifically unnecessary to consider consciousness as an emergent feature, we propose that the effort must be done in continuing building evidence and searching for data related with the main components of the conscious experience: data that have the potential to strengthen or refute the actual hypothesis, instead of trying to fit the emergent proposals in a process that does not require it to be explained.

5.1.3.   Second Hypothesis: Consciousness is at least a vertebrate function

The phylogenetic situation of the lamprey has been key to build a response to the last hypothesis. To prove its consciousness is to prove the possible consciousness of at least every vertebrate of the animal kingdom. But, although our results are reinforcing the proposal of Feinberg and Mallatt, we cannot establish definitive conclusions. What we can establish, is that, as it can be observed in Figure 4 (where we can infer every element of the INMC), there are general hallmarks and patterns of brain connectivity in lamprey that matches with the existence of perceptual structures and the temporal organization of the inputs. Considering the evidence that reveals the presence of illusions in fishes (therefore, top-down perceptual processes) and the multisensory convergence of different stimuli in lamprey (thus the necessity of organize the stimuli and interpret them), it is highly reasonable to consider the possibility of its sensory consciousness.

Thus, again, we propose that the more parsimonious approach to this question, as well as the more ethical, is to consider until proven otherwise that the lamprey fishes present evidence of consciousness.

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Figure 4. Scheme of the visual system of the lamprey with electrosensory participation from the octavolateral area
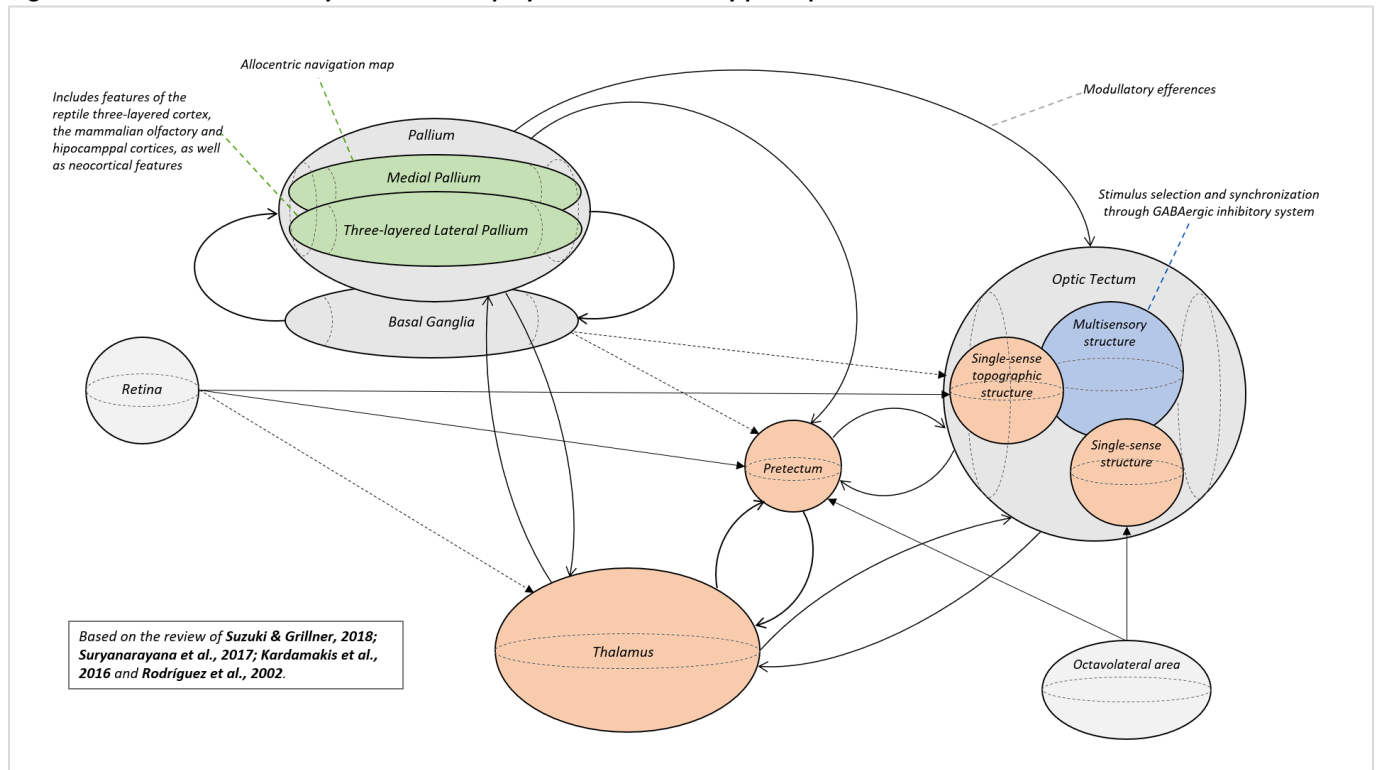

5.2. The Nature of Consciousness

What consciousness really is? And *Where can we find it?* These two starting answers have brought us to this final point. We defended through evidence our prototype of the INMC, therefore, we provided support to the postulates of the Neurobiological Naturalism, the Two-Stage Model and the Neuronal Global Workspace, and we established a mathematical skeleton of related variables through which consciousness can be explained. It seems that finally, consciousness is the fruit of a process shaped by evolution to deal with the multiplicity of sensory data: a multiple and unified receptor field that only accepts the significant and previously processed data.

To conclude this work, we introduce a final concept: the INMC Loop. This is, consciousness can be expressed as the full process of global perception in a specific time-window. But imagine an isolated organism that accomplishes all the structural and process requisites for consciousness that INCM established, in a timeframe of 500 ms, for example. Imagine, also, that this organism started its existence at the moment. The significance of the stimuli during the first 500 ms of its life will be at least, inferior to the significance of the last conscious percept of its life. This is, the organism will learn and will store information that will help it to classify, signify and provide valences to the components of its perception through its interaction with the environment along its life. Thus, consciousness is not only the encapsulated process inside this 500 ms but a continuous process of loops that include the two moments of perception. Every actual perception is the result of the anterior perceptual moment with the interaction of the new processed stimuli, as well as the collected memories and learnings established previously, that can modulate perceptions as internally triggered processes (see Figure 5).

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Figure 5. INMC Loop
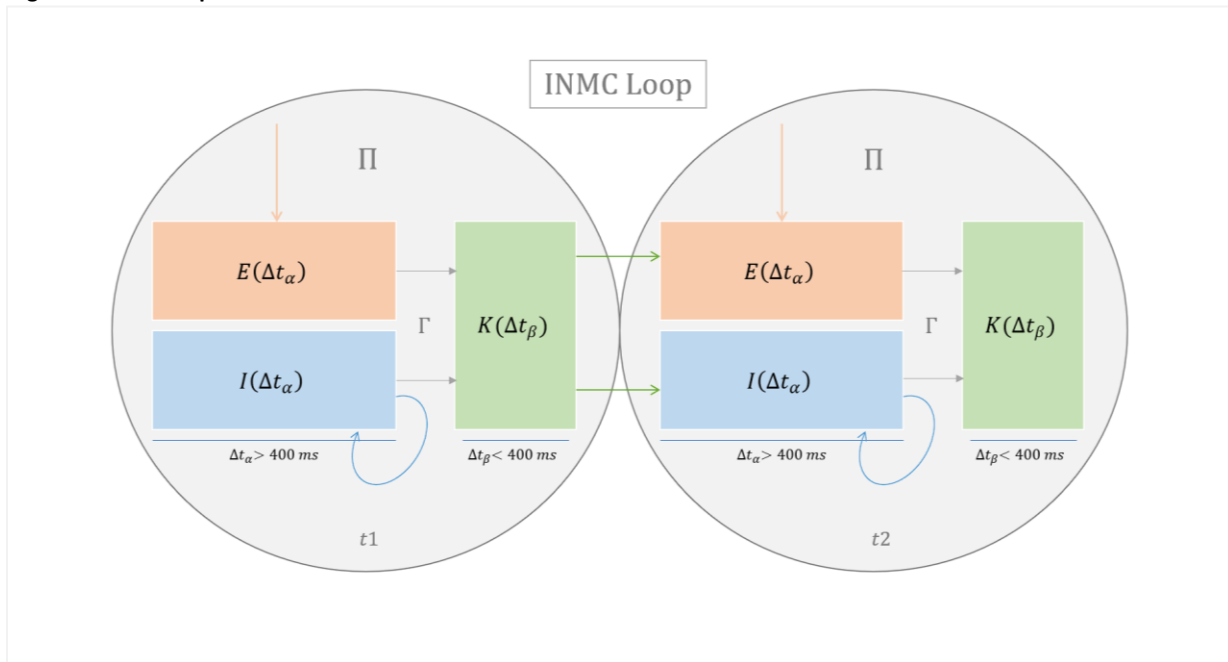
As other models propose, the perceptual patterns modulate the sensory pathways in a top-down way. This is highly compatible with the idea of prediction processing and it can also be observed in the connectivity of lampreys, where the pallium sends efferences to the optic tectum (see Figure 4).

5.2.1. The Ship of Theseus and the Philosophical Zombie

The philosophical implications of the neurobiological eliminatory approaches of the conscious experience are diverse. David Chalmers used in his book *"The Conscious Mind: In Search of a Fundamental Theory"* the concept of p-zombie to defend his property dualism through the illustration of a possible scenario where a human can be acting as a human without conscious experience (Chalmers, 2007; Cavanna & Nani, 2014). Our response to this movement is that the p-zombie is a fallacy originated in the misunderstanding of the neurobiological functions of the brains. A human cannot act as a human without perceptions: this is, without a system that contextualize the body, the environment and the significations of the integrated stimuli. This capacities, combined with highly elaborated functions in humans, as the verbal reporting capacity or the self-recognition, implies the conviction that what is perceived is different from the system that is perceiving, but our conclusion is that the processes of the system itself *are what is perceived*, and its relation with the external physical or chemical reality is simply a correspondence mediated by the receptors.

Thus, there is no necessity to explain *qualia* or the Hard Problem, because they are convictions, resulting thoughts of a system prepared through evolution to build its own representation of the world, inaccessible in other ways. The deep feeling of agency and the situatedness of the body in the environment are also results of neurobiological functionalities. While our brain is not the same thing in every moment, because its physical, chemical and biological dynamics, our sensation of continuity is provided by the long-term memories (our history) and the short-term memories (our actual context). We are embodied, isolated but constantly changing biological systems, and what really remains in us is the capacity of evoke in the present moment, experiences of the system that we were a second ago, or a year ago; in humans, remains the projection of us through our history, and the projection about us in the future

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(but the *sensory consciousness* itself could only need the short-term memory to generate context to the organism). Therefore, the *qualia*, or the Hard Problem, does not imply different qualities of the matter: they do not need to exist. The only that needs to exist is the capacity of the system to convince itself about the reality that is building. This is, the unique reality that can exist by a perceptive system is the perceived reality, trapped in an inescapable continuous process of cause-effect.

At the moment that we conclude that there is nothing essential or permanent in us but the convincement of the system about its agency, that is also a functionality based on the neural architecture and processes, we can suggest that consciousness could hypothetically be replicated, considering that a replicated system will share all the same convincements.

6. CONCLUSIONS

In conclusion, through this work we explored an option to build scientific knowledge about consciousness. Despite the objectives of the work are not fully accomplished because of the nature of the problem that we are approaching, we consider that we got as close as we could, and the most important, we offered theoretical support to great neuroscientific frameworks as the Neurobiological Naturalism or the Two-Stage Model.

Regarding the INMC, we deal with our own mathematical limitations and the lack of specificity, but we consider that the model could serve as a starting point to develop programming experiments, since it offers conjuncts which parts can be situated in a 3D space and in a specific timeframe, as well as the vagueness of the functions that we propose opens the door to a real mathematical and computational development. Thus, we are satisfied to have the opportunity to at least propose a first template of relationships that invites the scientific reasoning and participation.

7. AKNOWLEDGMENT

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8.1. List of boxes, figures and tables

Development of a first proposal on the INMC
Marçal Castán Sogas, March 2020

Bachelor's Degree Final Thesis
Universitat Autònoma de Barcelona
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APPENDIX

Dream, reality… The world's fallacy
— Josep Castán

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8.1 Extended development of the Integrative Neurobiological Model of Consciousness

By Marçal Castán Sogas, bachelor's degree in Psychology, Autonomous University of Barcelona. | Special contribution from Marta Alcalde Herraiz from the bachelor's degree in Physical Engineering at the Polytechnic University of Catalonia.

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VARIABLE DEVELOPMENT

1. **Structural variables**

   The central nervous system is a tridimensional system with neural hierarchical organizations: pathways, nodes and reticular structures of neurons with different capabilities of coding, processing and representing information. The structural variables refer to the organization of neurons in space, its synapses, its extension in a tridimensional plane and its type. For this reason, the structural variables determine the potential of the system to be conscious, but not determines consciousness itself. Despite the structure can reflect a chemical or physical compatibility between secreted neurotransmitters and membrane ligands, or a spatiotemporal disposition that can facilitate the fast communication between two neurons and isolate other cells, note that this variable does not refer directly to the time-specific neural chemoelectrical activity.

   1.1. **Operationalization**

   Single neuron location

   The tridimensional interconnected structure of our modelled conscious brain stablishes its minimal unit in neurons (u_i) where $i \in \mathbb{N}$ and classifies arbitrarily but permanently each neuron. At the same time, each neuron is situated in a specific point of the tridimensional space that takes x, y and z values. Thus, neurons can take the form: $u_i\ (x, y, z)$, where each coordinate is expressed in μm; where 0 is the exact center of each axis and the μm value indicates the deviation in micrometers of the point u_i from the center of the respective axis. For example:

   $$u_{101.758}(7.855, 3.601, 140.050)$$
   $$u_{32.000}(523, -15.890, -75.602)$$

   Synapsis

   The system stablished between two neurons through synapsis can be considered the function that relates both neurons in space. Thus, synapsis (s_n), where $n \in \mathbb{N}$, can be physically modelled by the following expression:

   $$s_n = s(u_{i1}(x_j, y_j, z_j), u_{i2}(x_j, y_j, z_j))$$

   Note that $i1 \neq i2$. While $i1$ stablishes the presynaptic neuron, $i2$ refers to the postsynaptic one. The information that contains the function allow us to stablish two interrelated points in the space and a preestablished direction of this relation.
   For example:

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$$s_1 = s(u_{101.758}(7.855, 3.601, 140.050), u_{32.000}(523, -15.890, -75.602))$$

By the moment, s_1 indicates that neuron 101.758, physically placed, is synapsed with neuron 32.000, also physically placed, and that 101.758 is the presynaptic neuron and 32.000 the postsynaptic one.

Neural network structure

Any function composition that includes more than one s can be conceived as a neural network (ω), where $k \in \mathbb{N}$, which takes the following form:

$$\omega_k = h(s_1, s_2 \dots s_n)$$

Where, for example, the simplest structure, a spatial-stablished loop between two neurons, can be expressed by the following functions:

$$\omega_1 = h(s_1, s_2)$$
$$\text{Where } s_1 = s(u_{101.758}(7.855, 3.601, 140.050), u_{32.000}(523, -15.890, -75.602))$$
$$\text{Where } s_2 = s(u_{32.000}(523, -15.890, -75.602), u_{101.758}(7.855, 3.601, 140.050))$$

Each ω represents a functional system. This is, it can contain nets of neurons with specific functionalities. Note that a neuron can be a part of different nets. And, in addition, note that this allows us to represent hierarchical structures with cumulative functionalities. In the following example, ω_1 could represent an inhibitory net, as well as ω_2 an excitatory one, and ω_3 a simple net that can determine the final state of a single neuron (see Fig.1).
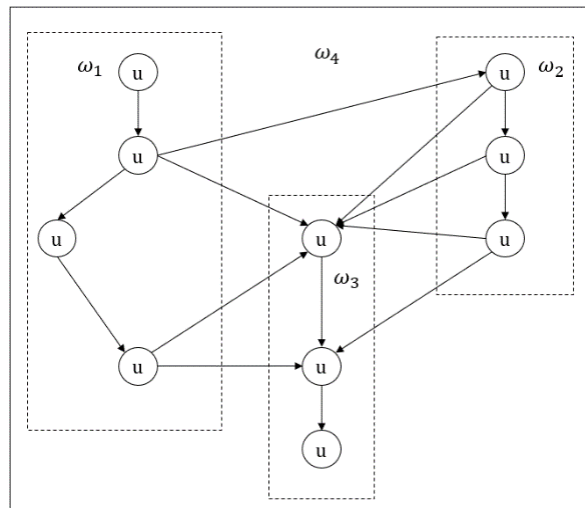

Figure 1. *Abstraction of a simple nested hierarchical network*

The entire system composed by ω_1, ω_2 and ω_3 can be expressed as $\omega_4 = \{\omega_1, \omega_2, \omega_3\}$ or also $\omega_4 = h(s_1, s_2, s_3 \dots s_n)$ where in this specific example $n = 15$. ω_4 can be classified, for example, as an ON/OFF system composed by an inhibitory structure, an excitatory structure and an integrative structure. Note that the specific activity of the ON/OFF is not determined.

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Global structure

The global structure reflects all the necessary circuits for an organism to be sensory conscious in the tridimensional space, including every neuron and every directed connection of the physical system. Thus, the full connectome needed by an organism to be conscious is expressed by:

$$\Pi = \{\omega_1, \omega_2 \ldots \omega_k\}$$

This stablishes an abstract representation of the necessary neural architecture, but again, not reflects any chemical or electrical activity; only the structural points and the preestablished cause-effect relationships in space.

Finally, our connectome can be conceived as the sum of every single minimal functional network, or the sum of large networks (build on minimal functional networks) with specific and crucial functions to build conscious perceptions. Thus:

$$\Pi = \{\omega_1, \omega_2 \ldots \omega_k\} = \{Top, Int, Val, Sal, Mem, Per\}$$

1.2. Topographic sensory structures with single-sense integration

The first crucial function of a sensory conscious organism is to stablish representations of what is happening into the body and in the environment. To do that, the system maintains a cause-effect concordance between receptors and single neurons. The first topographic neural maps will be a single physical correspondence between neurons and receptors through synapsis, and progressively, the combined information from different receptors will be merged across layers to put in relation the crude data.

Consider the following example: a simple visual circuit with 4 neural entrances u_1, u_2, u_3 and u_4. This circuit needs to provide an output that determines the existence of a single visual point or the existence of a line. First, we will need to stablish a correspondence between the input source and a neuron. This will imply a layer where there are neurons which activity correlate ≈ 1 with their bounded receptor, but every neuron is isolated from the effects of the other receptors. With the crude data conserved and entered to the system, it can start a process of integration. In our abstract example, the topographic layer that corresponds to the neural entrances (see Fig 2.) will stablish synapses with all the neurons required to determine the position of the dot; this is, the activity of the neurons in the very previous layer will explain a big part of the variability of the integrative layers. In figure 2, the activity of u_8 will depend mostly on the activity of u_4 but the activity of u_9 will depend on the activity of all the previous neurons. Note that correlation can be obtained by the Pearson's Coefficient formula applied to a specific sample of electrochemical activity between two neurons in a specific time:

$$r_{xy} = corr(x, y) = \frac{n \sum x_i y_i - \sum x_i \sum y_i}{\sqrt{\sum x_i^2 - (\sum x_i)^2} \sqrt{n \sum y_1^2 - (\sum y_i)^2}} = \frac{cov\,(x, y)}{\sigma_x\,\sigma_y}$$

If applied to our notation, where the specific electrochemical response activity of a neuron can be conceived as $u_i Act$, where i corresponds to the number that classifies the neuron in space, and considering an hypothetically infinite sample of performances over time, we can determine:

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$$r_{u_iAct_x,u_iAct_y} = corr(u_iAct_x, u_iAct_y)$$

Thus, a linkage between two neurons can be expressed as physical or as correlational:

$$s_n = s(u_{ix}(x_j, y_j, z_j), u_{iy}(x_j, y_j, z_j))$$
$$r_{u_iAct_x,u_iAct_y} = corr(u_iAct_x, u_iAct_y)$$

Returning to the example, we provided an abstraction of how can be conceived the architecture of the topographic maps. It is important to consider that the topography is the first step to encode specific stimuli, and progressively, through the hierarchical levels of the single-sense processor, the information will be merged to increase its significance.
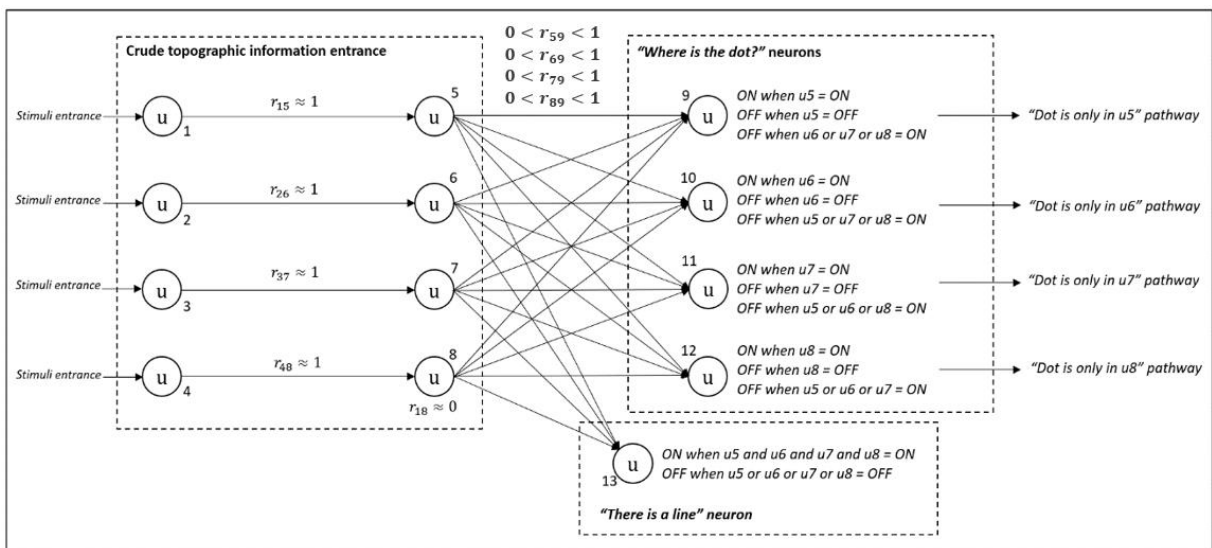

Figure 2. Abstract example of a minimal sensory integration through topographic single-sense map

Concluding the section, the topographic structures with single-sense integrative pathways (Top) will be considered all the neural network structures (ω) where the activity of every neuron of its architecture depends on the activity of a neuron directly linked to a specific receptor, without considering the correlative relations with neurons linked to other senses: $Top = f(\omega_i \ldots \omega_l)$

1.3. Multisensory integration structures
Unlike the previous one, the architecture that allows the integration of multisensory data can also be described as the neural systems that hierarchically integrates and processes combined information of different senses through pathways with specific encoding functionalities. Thus, the multisensory structures of the brain are these structures with neurons where its behavioral variability depends at least on the variability of two types of receptors from different senses.

Consider the following example: as well as the previous presented structure, we have a similar one that allows us to position the own body in a space of 4 zones (see Fig.3). If we combine the visual data that indicates where the point is, and the proprioceptive data, that indicates where the body is, we can position one in relation to the other. Consider that u_1 have been stimulated and u_2, u_3 and u_4 not, and consider that u_{13} have been stimulated and u_{14}, u_{15} and u_{16} have not. First, u_1 will activate u_5, that at the same time will activate u_9, while u_{10}, u_{11} and u_{12} are

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inactive. In parallel, consider that u_{13}, from another sensorial organ, is stimulated. u_{13} will activate u_{17}, that will activate u_{21} while u_{22}, u_{23} and u_{24} will be inactive. Four neurons in a multisensory layer encode the meaning *"I am at zone 1"* so the four neurons will receive stimuli from u_{21}. At the same time, each of the four neurons receive one specific input from the visual sense. Concretely, u_9 have synapsis with u_{25} inside this complex. The reception of both stimuli will activate a neuron that encodes the convergence between the dot and the body at the same zone.
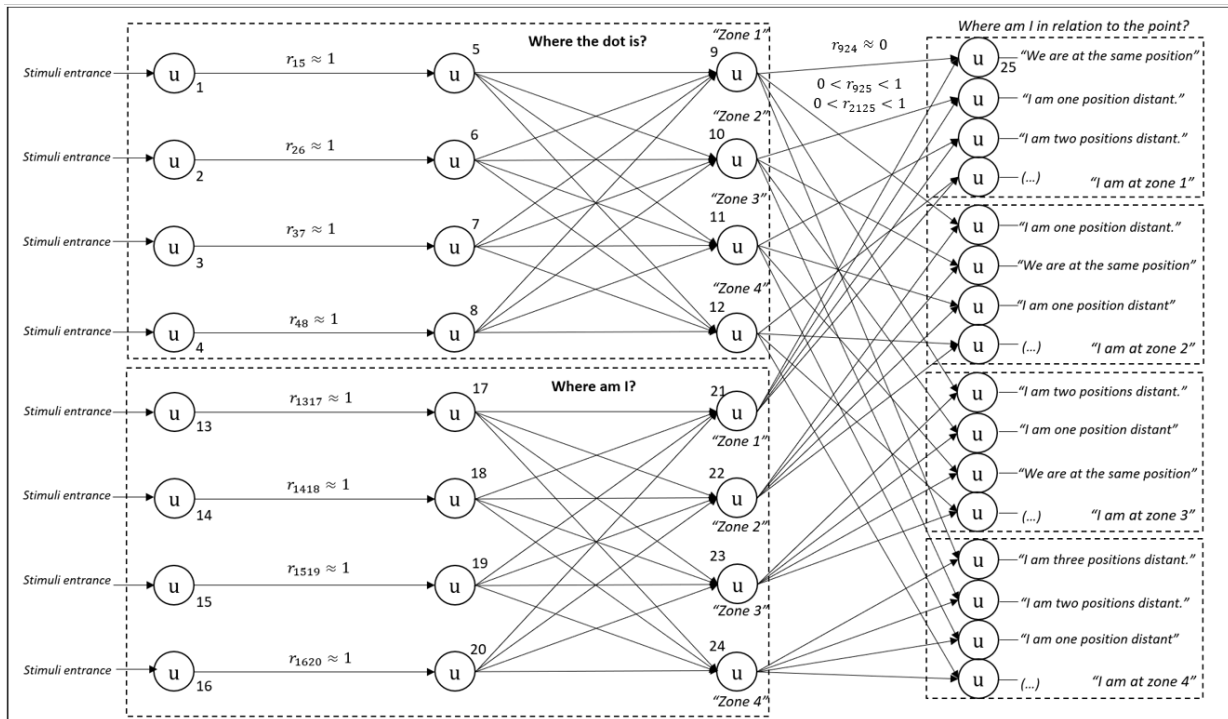

Figure 2. *Abstract example of a minimal multisensory integration between two type of senses*

Thus, we can define the multisensory architecture of the brain (Int) as the circuitry (ω) which the variability of the neuron's behaviour is explained by the effects of at least two different inputs providing from two different senses or more, with highly integrative layers where the variability of the behavior of its neurons can be explained by many inputs from many senses: $Int = f(\omega_r \dots \omega_s)$

1.4. Valence coding structures, Salience coding structures, Memory structures

A sensory stimulus, although highly integrated, cannot be representative to an organism without a layer of processing that indicates its peril, its neutrality or its benefit. This classification allows the organism "fight or flight" behaviors, "wait and see" behaviors or approach behaviors in front of the stimuli. Moreover, this classification must grant the system the capacity to recognize the stimuli with major consequences in each sequence of perception, that will include a lot of different processed data. To discern between stimuli and constantly adjust the behavior in front of them, the organism must keep previous classifications over time. Note that we have described abstract concepts classified by psychology as appetition and aversion, attention and memory, but highly operable when observed through neural functions and the lens of evolution. Note that the classificatory functions of the neurons, its systematic capacity to discern relevant stimuli and its

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capacity to store information proceed directly from its cellular qualities: its maintenance over time, but characterized by a plastic capacity of stablishing new synapsis, discard unused pathways and strengthen the relevant ones. Although by the moment it's hard to define the specific qualities of the networks with these functionalities, we can find neurobiological hallmarks and behavioral evidences of this capacities that explains the ability to the system to attribute valences to the stimuli, discern the most determinant stimuli between a set of many others, and store information to adapt behavior in future situations. Thus: $Val, Sal, Mem = f(\omega_m \dots \omega_n)$ where Val represents the neural architecture that allows the valence coding, Sal stands for salience coding architectures and Mem for mnemonic specific networks. Note that these are three structures that are presented together because its mutually dependence during a percept.

Finally, as Feinberg and Mallatt suggested (Feinberg & Mallatt, 2017), we propose that every organism that can be operantly conditioned is provided with these functional capacities with high implications on sensory consciousness.

1.5. Perception coding structures

The discovery of the temporal-discrete performance of conscious perception, but the knowledge that their frameworks capture encoded all the quasi-continuous integrated data, raises the necessity of the existence of a system with the capacity to put in relation all the highly integrated and processed data in a specific moment. This is, the pre-perceptual sensory information needs to be held until is organized, encoded and sent to the perceptual structures. The Two Step model explains that the duration of a conscious precept and the temporal resolution of the senses are different issues (Herzog et al., 2016), so, the necessity of a widespread architecture that encodes and represents the final global sensory perception is evident.

The specific structures involved in this process are vaguely understood by the time, since it must be a reticular widespread net that entangles many associative areas in large brain connections, but the specific process of encoding perceptions through these architectures is unknown, but present, since we know that, for example, we have areas involved in the time or motion perception that differs from the simple juxtaposition of inputs in a receptor field. What we know, is that the activity of the architecture will be subject to neural oscillations that in humans, when conscious, are between beta and gamma waves, and will be compatible with top-down processes of sensory modulation or prediction.

Although being an inoperant definition, we still can define this architecture as an indefinite set of neural networks with the previous explained qualities:

$$Per = f(\omega_j \dots \omega_k)$$

Finally, it is important to remark that the existence of perceptual architectures does not imply the existence of a single area or a single net composed by neurons fully dedicated to the perceptual processes. What we suggest is the probable existence of specialized networks that works together with other networks that overlaps different functions and encodes different features: this is, inside $Per = f(\omega_j \dots \omega_k)$ we will find neural networks that probably are present too in, for example, $Int = f(\omega_r \dots \omega_s)$.

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2. Time-window

As it is demonstrated, conscious perception depends on two specific time windows. This is a crucial variable, the base of the Two Stage model, and a dimension that Feinberg and Mallatt not explored in the Neurobiological Naturalism, since is an approach not based on the real-time functionality of conscious brains but in the common neurobiological characteristics of conscious ones.

2.1. Operationalization

The first time-window on the process of consciousness is the time window related to the non-perceptual processes itself. This is, the first time-window is the time that brain uses to collect sensory data, integrate it, give it valences and interpretations, and prepare it to be attracted to the perceptive pathways (Herzog et al., 2016). Thus, this pre-conscious time window (Δt_α) can be conceived as the sum of its fractions (Δt_m), where the neural processes takes place. Note that $m, w \in \mathbb{N}$ and indicates a fraction of Δt_α, which can take a value $\Delta t_m < 400ms$ or a value Δt_w inside a fraction Δt_m. Thus:

$$\Delta t_\alpha = \{\Delta t_{mn}\} = \{\Delta t_{m1}, \Delta t_{m2}, \Delta t_{m3}, \dots\}$$
$$\Delta t_m = \{\Delta t_{wn}\} = \{\Delta t_{w1}, \Delta t_{w2}, \Delta t_{w3}, \dots\}$$

Then $\Delta t_\alpha > 400ms$
Then $\Delta t_m < 400ms$
Then $\Delta t_w < \Delta t_m < \Delta t_\alpha$

The second time window is the duration of a perceptual experience (Δt_β). By the time, it cannot be defined as well as the previous one because a lack of data, but we can infer its lesser duration in relation to Δt_α, so:

$$\Delta t_\beta = \{\Delta t_{bn}\} = \{\Delta t_{b1}, \Delta t_{b2}, \Delta t_{b3}, \dots\}$$
$$\text{Where } \Delta t_\beta < 400ms \; ; \Delta t_\alpha \neq \Delta t_\beta$$

Finally, the time window structures the order of the successes that give rise to a conscious experience. In a hypothetically and theoretical case, Δt_β is the first timeframe in which the arriving inputs are processed, and Δt_α is the time in which the results of these first cause-effects are compiled and decoded by the perceptual architecture. If this cycle is completed by a system, we can argue that it has been conscious during, for example, 0.5ms? Not at all. Our integrative proposal needs a final step that will be discussed in the final section of this prototype.

3. Externally triggered processes

By the time, we described what kind of structure is necessary to perceive consciously, and what is the time window in which this can happen. But although we situated our model in a spatiotemporal structure, we need a form to describe the specific processes that will trigger the change between Δt_α and Δt_β. In this direction, we can differentiate two processes that will take place during Δt_α; externally triggered processes and internally triggered processes. This is, the stimuli-response specific neural patterns that Δt_α will include through Π.

3.1. Operationalization

The externally triggered processes, or $E(\Delta t_\alpha)$, are the resultant set of neural electrochemical activity provoked by stimuli from the external senses (body or environment) interacting in a cascade of stimuli-response activity between neurons. The first step on this process is the neural

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reception of the encoded stimuli, that normally is triggered by a sensorial receptor. This will provoke an initial neural response ($res_i(\Delta t_{wn})$) that will produce a specific pattern of activation ($e_i(\Delta t_{mn})$). This is, theoretically assuming the full physical, chemical and biological characteristics of Π, the resultant $E(\Delta t_\alpha)$ can be predicted by the time that we can predict the behavior of every ω given a first cause or input ($inp(\Delta t_{wn})$). In other words, the specific interaction between a first specific neuron $u_i(x, y, z)$ and a specific encoded input from a specific receptor $inp_i(\Delta t_{wn})$ will trigger a cascade of stimuli through a neural network ω_i shaping the form of a specific pattern of activations $E(\Delta t_\alpha)$. This is:

$$E(\Delta t_\alpha) = \{e_i\} = \{e_1, e_2, e_3, \dots\}$$

$$\text{Where } e_i(\Delta t_{mn}) = e(res_i, \omega_i)$$

$$\text{Where } res_i = res(inp_i(\Delta t_{wn}), u_i(x, y, z))$$

This also explain to us that the modelled architecture Π needs to include specific variables related to the chemical and electrical dynamic of every neuron, and the physical and chemical dynamics of the synapsis to explain the specific activity of the circuit and the time used to reach the deepest layers (membrane resistance, distance between neurons, etc). By the time, this escapes from our little knowledge, but would be a great improvement for the model reaching a mathematical definition of the e function.

4. **Internally triggered processes**
In parallel to the externally triggered processes, a Δt_α must include inherent neural activity. This "actual" activity can be originated in a previous moment by stimuli-response patterns, and the Δt_α simply traps inside the moment the first neuron activated on its timeframe. Other causes of activation, no directly triggered by a previous neuron, can be also interpreted as the first cause of internally triggered processes, like cell clocks or chemical dynamics, including the effects of the glia, the maintenance of neurotransmitter in the synaptic space, etc.

4.1. **Operationalization**
Its operativization follows a parallelism with the previous processes. In this case, the internally triggered processes $I(\Delta t_\alpha)$ does not depends on an external input but depends on internal first causes $ins(\Delta t_w)$. By the rest, its operativization follows the same structure:

$$I(\Delta t_\alpha) = \{v_i\} = \{v_1, v_2, v_3, \dots\}$$

$$\text{Where } v_i(\Delta t_{mn}) = v(inn_i, \omega_i)$$

$$\text{Where } inn_i = inn(inp_i(\Delta t_{wn}), u_i(x, y, z))$$

4.2. **Spatiotemporal synchronization**
While this model cannot explain how every neural network must behave to generate significant data, like the example of the structural variables, it is necessary to include in the INMC a restrictive variable. This is, we can have a perfect structure Π prepared to perceive, and we can have externally triggered processes and internally triggered processes through the structure, but if these processes are disordered spatially or temporally, the processing coherence will be lost. Thus, we stablish Γ, the

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spatiotemporal synchronization of the processes, as an essential feature of the perceptive process. We aim to remark the incapacity of this model to introduce more operativization by the time, and we defend that this is a variable that in a hypothetical development of the model will be lost thanks to the deep understanding of the systemic relations between neurons through electrochemical stimuli-response activity.

5. **Perceptive patterns**
Finally, the internally and externally triggered patterns will reach what Herzog called an attractor state (Herzog et al., 2016). An integrative point that triggers the stimuli to generate, through the disposed brain architecture, the specific patterns that encodes the final moment of perception. The global, combined, unified and significant information, entangled in a non-specified-by-the-moment structure that encodes sensory and internal data to generate a meaningful lapse of time. In a little fraction of a second the information of at least the previous 400ms will be broadcasted in a long-range structure in compacted bites. This is, the perceptive architecture does not process again all the hierarchical integration: we don't perceive movement as a progression of dots in our visual field, we perceive movement as an attributed characteristic that certain neural networks constructed thanks to the dot-by-dot sensory input (Herzong et al., 2016). We propose, moreover, that the encoded and signified data that enters to the perceptive structures is the data that will we recorded and maintained through memory structures instead of the full amount of single sensory inputs.

5.1. **Operationalization**
Thus, perceptive patterns $K(\Delta t_\beta)$ will be the result of the spatiotemporally synchronized (Γ) previous internally and externally triggered processes, $I(\Delta t_\alpha)$ and $E(\Delta t_\alpha)$, through a structure Π. Then:

$$K(\Delta t_\beta) = K(E(\Delta t_\alpha), I(\Delta t_\alpha), \Pi) \cdot \Gamma = \{k_n\} = \{k_1, k_2, k_3, \dots\}$$
$$\text{Where } k_n = k(e_i(\Delta t_{mn}), v_i(\Delta t_{mn}), \omega_j) \cdot \Gamma$$

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