



Organ Failure: A Computational Model and Perspective

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Abstract

Organ failure in biological systems is perceived as a physiological failure which is addressable via organ transplantation. Transplantation is challenging when donor organs are not easily available. Therefore, the development of a perspective capable of yielding potential therapies is required. The presented research addresses this problem and considers the biological system's poly-computing capability. The proposed solution considers that the organs are biological computing nodes. It considers that organ failure arises when biological computing nodes don't perform their expected function. The proposed approaches are the micro-brain and macro-brain consciousness paradigm (MMCP) and evolutionary consciousness paradigm (ECP). MMCP and ECP describe aspects concerning the relations, synaptic evolution, communication, and adaptation to handle multi-sensory inputs. The research describes how MMCP and ECP influence technology and application development. Furthermore, performance evaluation is done to investigate the operational duration of the concerned biological entities. Analysis shows that using the proposed approach enhances the operational duration by an average of (25.2–54.1)%.

Keywords Biological systems · Paradigms · Intelligent systems · Consciousness · Integration points · Brain

1 Introduction

Artificial intelligence approaches have transformed technologies such as communication networks [1–4]. This can be seen in the increased use of algorithms such as artificial neural networks [5, 6]. Advanced learning mechanisms and paradigms such as learning diversity and metacognition enable the realization of intelligent entities [7–9]. The discussion in [10] considers the realization of a conscious agent via the cognitive radio. The cognitive radio evolves

from a similar entity with metacognition to an entity having consciousness.

The design in [10] has been motivated by the claustrum's role in consciousness. The claustrum plays a critical role in the conscious capability of intelligent entities [11–13]. It executes multi-sensory input information integration [14, 15]. Hence, the view in theories such as the integrated information theory (IIT) and related work is that consciousness is a result of the existence of rich data domains. The discussion in [10] considers that a conscious agent with a single brain can execute a transition between multiple conscious states. The discussion in [1–10] describes how the advances in understanding biological systems has enabled the realization of biologically motivated techniques and solutions.

The concerned area in [1–10] has focused on the aspects of computing networks. In addition, the discussion in [1–10] has not considered the aspects of biological poly-computing. Biological poly-computing is identified in [16] to infer that organic material can be considered to act as computers. Therefore, organs in biological systems can be considered to be computers. Hence, the occurrence of organ failure can be considered not to be the failure of a single event but that of a network malfunction (The occurrence of organ failure can be considered not as the failure of a single event but rather as that of a network malfunction). From the perspective of

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biological poly-computing, the emergence of consciousness via information integration fuses multi-sensory input. However, an understanding of the biological system from the perspective of organs being minicomputers in a network requires further consideration. Such a perspective enables consideration of organ failure as the occurrence of malfunction in the multi-sensory input. Therefore, the occurrence of organ failure can be considered a fracture in the consciousness of the biological system. The allusion to consciousness is based on the notion that it arises due to information integration as executed by the Claustrum. This has led to the IIT, an insight found to be of value in [10–13].

Therefore, it is important to design a framework that supports a poly computing perspective of the biological system. The framework is designed to explaining the relations between the organic poly-computers that constitute the biological system. The framework provides an alternative to examining the occurrence of organ failures in the biological system. It is designed based on the cognitive radio perspective. A consideration of the cognitive radio perspective enables the development of a signal driven view of the biological system. This is beneficial in potentially tackling challenges that may arise in the biological system. A multi-brain consideration enables the introduction of approaches that address brain-stimulation. Hence, the study presents a novel perspective known as cognitive radio-driven neuroscience (CRDN).

1.1 Research Contribution

The paper presents a cognitive and poly-computing perspective of the biological system. The presented research alludes that organ failures are not solely due to physiological mechanism anomalies. Instead, the proposed algorithm considers that organ failure arises due to failure in the networks between the biological's system poly-computer networks. The interactions between the network of biological poly—computing nodes explained via the proposed CRDN perspective. The CRDN perspective presents a computational perspective enabling an improved understanding of relations between biological system entities. (The CRDN perspective provides a computational framework for better understanding the relationships among biological system entities). The perspective considers the occurrence of consciousness via the incorporation of integration points and intercommunications. This is done with a view to mitigating the occurrence of organ failure the research contributions are enumerated as:

First, the paper proposes the CRDN as a bridge to enable the derivation of paradigms enabling a computational analysis of organ failure in biological systems. The research recognizes that complex biological systems execute information integration at different scales. At a lower scale, a small

capacity claustrum (and information integration) is located within a micro-brain system. A large capacity claustrum (and information integration) is located within a macro-brain system. The biological system is described via relations between the micro-brain, and macro-brain. CRDN embodies the micro-brain, and macro-brain consciousness paradigm (MMCP). In MMCP, information integration emerges from varying patterns of interactions between logical synapses associated with the micro-brain, and macro-brain.

1. First, the paper proposes the CRDN as a bridge to enable the derivation of paradigms enabling a computational analysis of organ failure in biological systems. The research recognizes that complex biological systems execute information integration at different scales. At a lower scale, a small capacity claustrum (and information integration) is located within a micro-brain system. A large capacity claustrum (and information integration) is located within a macro-brain system. The biological system is described via relations between the micro-brain and macro-brain. CRDN embodies the micro-brain and macro-brain consciousness paradigm (MMCP). In MMCP, information integration emerges from varying patterns of interactions between logical synapses associated with the micro-brain, and macro-brain.
2. Second, the paper proposes that the information integration functionality in the micro-brain and macro-brain has evolutionary capacity. The evolutionary capacity incorporates integration point evolution. The consideration enables the development of new views to extend the current understanding of the human biological system. The synthetic perspective enables the development of new potential applications. The integration point comprises multiple evolving interfaces. The incorporation of interface evolution leads to the integration point having a dynamic capacity. The dynamic capacity leads to a variation in the information integration capacity and evolving consciousness (This dynamic capacity results in varying information integration capacity and evolving consciousness). The research presents the evolutionary consciousness paradigm (ECP). In the ECP, the evolutionary capacity enables the micro-brain and macro-brain to have varying inputs and outputs thereby exhibiting robust and complex behaviour. The pattern of information integration emerges from integration point evolution and integration point de-evolution. In this case, evolution is the capability of the intelligent agent to develop an integration. De-evolution indicates the dis-allowing (preventing) of the development of the integration point. The integration point evolution and de-evolution are enabled by integration point editing.
3. Thirdly, the research formulates a model based on the equality criterion for the proposed CRDN. The model

embodies the perspective of evolving integration points. The equality criterion considers nerve endings and proximal structures as enabling communications between biological poly-computing nodes. The equality criterion is motivated by the need for two communicating entities (biological poly-computers) to have an equal number of mediating wired channels. The model provides future directions to brain-related domains such as neurosurgery and neural editing technology applications. This is due to emerging trends of technological convergence in neural editing and brain engineering [17, 18]. In addition, the presented research formulates the biological entity i.e., related organ's operational duration. A longer operational duration is deemed more beneficial than a shorter duration as it signifies more epochs of the organ executing its functionality. Furthermore, performance evaluation is done (conducted) to investigate the performance benefits given the use of the proposed approach.

The rest of the discussion is structured as follows. Section 2 focuses on existing and background work. Section 3 discusses the proposed MMCP. Section 4 focuses on the proposed ECP. Section 5 presents the mathematical formulation associated with the equality criterion. Section 6 describes the application of MMCP and ECP. Section 7 presents the results of the performance evaluation. Section 7 is the conclusion.

2 Background and Existing Work

Hu et al. [19] focus on developing a computational model for examining kidney function in a diabetic individual. The developed model uses data on the glucose volume being transported in diabetic and non-diabetic scenarios. It examines the functionality of renal transport of key solutes. The overall objective of the study is the derivation of an extended computational model of the human kidney. The computational model derived from the observed biological transport data describes kidney epithelial transport for a diabetic patient. Similar data driven kidney computational models can be found in [20, 21].

Wang et al. [22] note that the kidney is controlled by efferent and afferent nerves that run around and in the outer layer of the renal artery. It is also noted that afferent renal sensory nerve and efferent renal sympathetic nerve interact via a pathway mediated by norepinephrine. The rest of [22] examines how the kidney's different pathways involving multiple channels and receptors and their interaction to enhance the understanding of the occurrence of acute and chronic kidney disease. The discussion in [22] has not considered that the interaction of multiple afferent and efferent nerves can lead to the emergence of another

brain (besides the brain in the central nervous system). This perspective is important as the brain at the focus of the central nervous system is realized via an assembly of connected and communicating neurons interacting in biological neural networks. However, a consideration of the emergence of a brain in the kidney or any other critical organ requires further research attention.

The study in [23] notes acute kidney infection leading to negative outcomes necessitating kidney transplant leads to individual cognitive decline. The observed decline occurs as mild cognitive impairment and dementia. An interruption in normal renal functioning negatively influences human cognition. This implies the existence of communication via a set of mechanisms. A framework enabling a probable study of these communication mechanisms has not been considered. Instead, the focus in [23] is on studying the relationship between kidney transplantation and cognition. A similar perspective can be found in [24, 25].

Donato et al. [26] note that the brain's dopamine system influences dopamine levels which influences neuropsychiatric conditions. This influence on the psychiatric state implies that an individual's conscious state and the role of the claustrum are influenced by the brain's dopamine system. Therefore, the neurons associated with the brain dopamine system are linked with the brain, kidney, and human consciousness. However, a study of the underlying biological system considering the role and influence of consciousness has not received attention in [26]. The consideration of the notion of consciousness arising from the discussion in [26] requires developing a new perspective on the biological system being considered. Though necessary, the research in [26] has not been presented in this direction.

Signorelli et al. [27] recognize the need to develop new perspectives for understanding consciousness in biological systems and models. The presented perspective opines that biological systems comprising living beings were previously perceived only as merely cells and neurons. This consideration advances the existing perspective of using computing metaphors. In this case, the computing metaphors are closely linked to information coding, processing, and information communication. However, further improvement can be obtained by using the metaphor of an evolving life form and its extensible functionality for advancing the need to develop a new perspective for improving the understanding of human biological systems. This notion of consciousness and its associated functionality has not been considered in [27]. Instead, Signorelli et al. [27] have examined different forms and contexts of consciousness. Such a notion leads to the need to consider an evolving biological system. This perspective has received consideration in [28]. However, a path of considering this evolution alongside the role of consciousness is yet to receive significant research attention.

3 Proposed Micro-brain Macro-brain Paradigm (MMCP)

CRDN considers that the cognitive radio in making use of bio-inspired mechanisms presents a robust system capable of enabling an understanding of biological systems. In CRDN, an organ of the biological system comprises two aspects i.e., the physiological aspect and the computational (non-physiological) aspect. The two aspects execute concurrent poly-computation. Being concurrently poly-computational, the physiological and computational aspects execute multiple different tasks at the same time. The perspective showing the organ of the biological

system comprising the physiological and computational aspects is shown in Fig. 1.

Figure 1 has two subfigures i.e., Fig. 1a, b. Figure 1a presents the current and existing perception of a biological organ. In this case, the biological organ only has the physiological aspect. Such a perception deems the biological organ as comprising a significant combination of self-regulatory mechanisms. Figure 1b shows the proposed perception of the biological organ. It presents the physiological and computational aspects each having its own set of biological poly-computing nodes. The scenario in Fig. 1a, b shows that the existing and current perception support poly-computing node heterogeneity. However, the proposed perception in Fig. 1b shows that the biological organ incorporates a higher level of poly-computing heterogeneity. In Fig. 1b, there is a

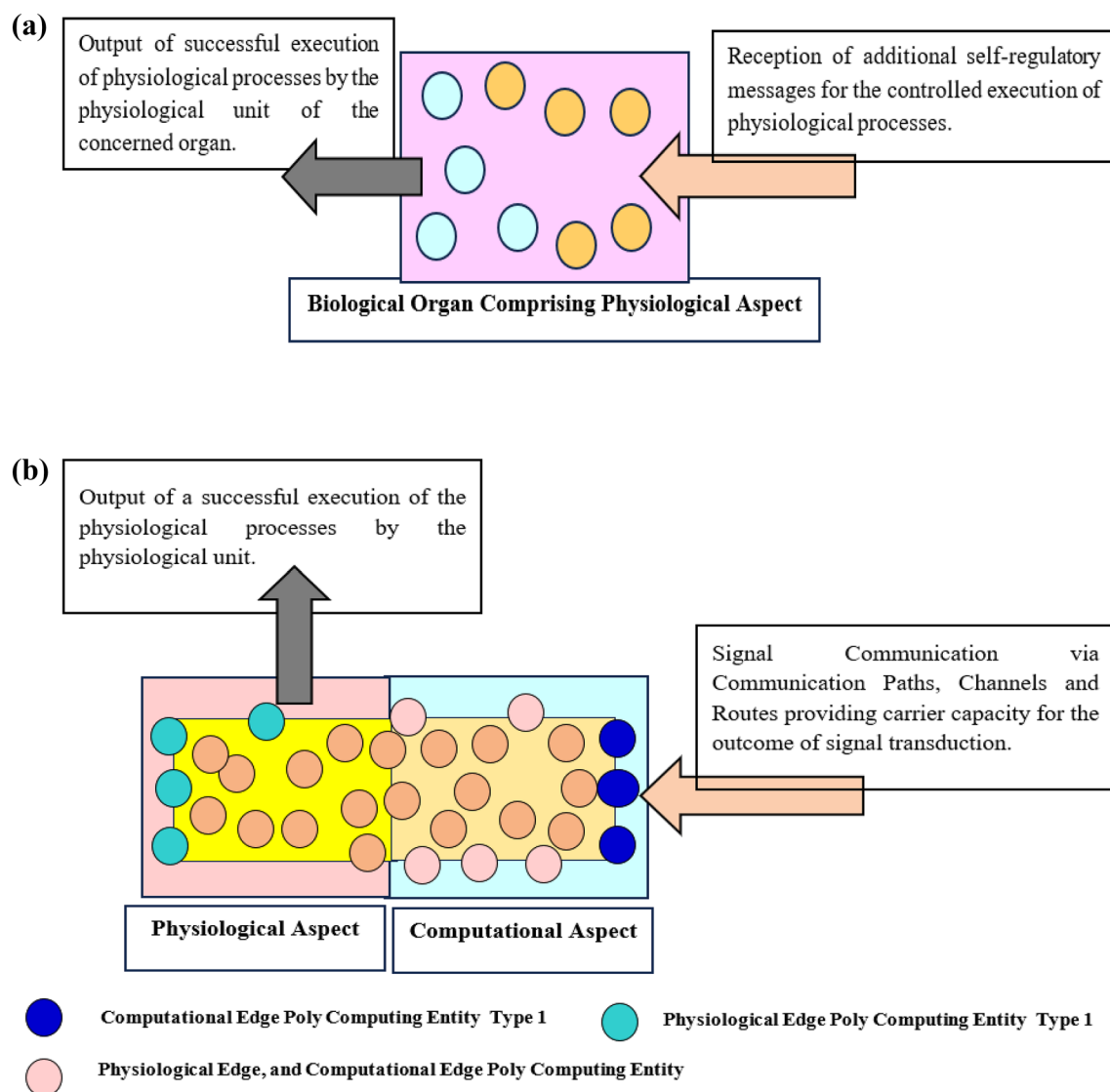


Fig. 1 **a** Current perception of biological organ that focuses only on the existence of the Physiological Aspect. **b** Proposed perspective showing the Physiological Aspect and Computational Aspect with multiple poly-computing enabling entities

higher level of poly-computing heterogeneity due to the need to ensure inter-communications. The inter-communications arise between the physiological aspect and the computational aspect. Such inter-communications is not necessary in the current perception and approach.

Figure 1a shows the existing perception of a biological organ's functionality and role. In this presentation, the biological organ has only a physiological aspect. The concerned biological organ in this case receives messages i.e., instructions regarding the execution of self-regulatory mechanisms. The self-regulatory mechanism enables the realization of physiological processes. For example, the kidney an important organ receives self-regulatory messages from the hypothalamus (which produces the anti-diuretic hormone). The anti-diuretic hormone works in conjunction with the kidney's self-regulatory mechanisms to execute the desired function. In Fig. 1a, the desired function leads to the production of output indicating a successful execution of the physiological processes by the kidney's physiological unit. In the existing approach, the concerned biological organ requires physiological aspects to execute the desired functionality. In this case, the consideration of the signal transduction considers only a single dimension. In the presentation of Fig. 1a, the use of different colours are intended to demonstrate that the kidney or any other concerned biological organ executes multiple functions.

The case in Fig. 1b shows the perception of the biological organ as being proposed. The biological organ in this case comprises a physiological aspect and a computational aspect. The physiological aspect in this case executes the task of filtration without considering the communication between the hypothalamus and the kidney for the use of the anti-diuretic hormone. In a similar case to Fig. 1a, the physiological aspect is oblivious of the regulation of the pathway influencing communications between the hypothalamus, and the kidney. However, the introduction of the computational aspect with the inclusion of the associated cognition. The introduced cognition increases the awareness and configuration of the parameters associated with the communication mechanisms between the kidney and the hypothalamus. In this case, the consideration of the signal transduction is multi-dimensional. Similar to Fig. 1a, the use of different colours is also applicable. The use of multiple and different colours demonstrates that the kidney or any other concerned biological organ executes multiple functions.

In MMCP, the biological organ is deemed to comprise the physiological unit and computational unit. The computational aspect of the organ and its poly-computing entities constitute the micro-brain. This is the underlying perspective in MMCP. In MMCP, biological systems with multiple critical entities such as the heart and kidney have their own biological poly-computer, and information integration (and consciousness context). Cognitive cardiology emerges

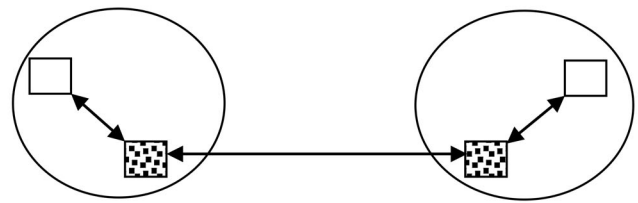


Fig. 2 Micro-brain relations

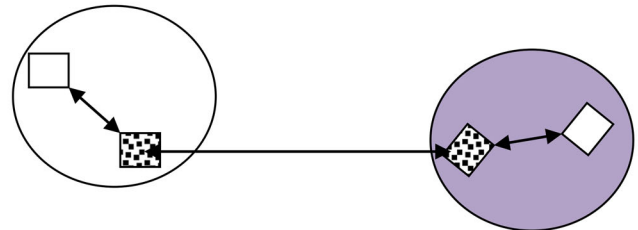


Fig. 3 Micro-brain and macro-brain relations

because of the discovery that the heart has its own brain as seen in [29, 30].

In the communication system (cognitive cardiology), the heart-associated brain (called the micro-brain) is separate from the brain at the center of the central nervous system. The central nervous system associated brain is the macro-brain (the conventional brain). The concepts associated with cognitive nephrology can be inferred (associated with another critical entity i.e., the kidney). In cognitive cardiology, the micro-brain and macro-brain are in the heart and at the center of the nervous system, respectively. Cognitive nephrology has its own entities of micro-brain and macro-brain. In this case, the micro-brain and macro-brain is in the kidney and at the center of the nervous system, respectively.

For the contexts of cognitive cardiology and nephrology, the micro-brain engages in internal sensory information communication and integration. The integration and communication are done to realize the regulation of the critical entity. Each micro-brain can identify external integration points. These integration points can be found in other micro-brains or macro-brains. Therefore, each micro-brain and macro-brain can have multiple and linked integration points. The functionality of the integration is executed by logic that is embedded in the micro-brain and macro-brain. The logic executes the functions of external integration point identification, selection, and communication.

In MMCP, consciousness emerges from the relationships between micro-brains or macro-brains or integration points. The occurrence of information integration in this case is contextual. The integration involves (1) Micro-brains, (2) Macro-brain and micro-brain and (3) Macro-brain relations as presented in Figs. 2, 3, and 4,

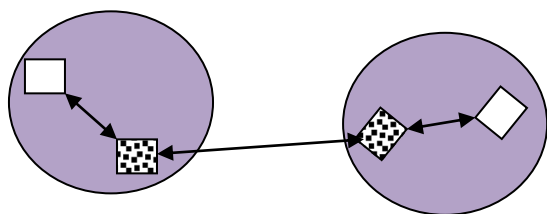


Fig. 4 Inter macro-brain relations

respectively. Each of the contexts involves communications between the micro-brain, and macro-brain. The communications are realized via logical synapses. Each entity in Figs. 2, 3, and 4 forms a logical synapse via synaptic element combination. Information integration (and consciousness) in MMCP considers logical synapse formation as part of the consciousness procedure.

The interaction between external integration points enables neural load migration and functional portability. Neural load migration (NLM) refers to a case where sensory inputs associated with the micro-brain or macro-brain utilize the integration point of another brain entity. NLM becomes necessary when there is an increase in the number of inputs for a given brain entity. This occurs in the event of over-stimulation of the sensory inputs associated with the integration point of a given brain entity. Input processing from the over-stimulation uses processing resources in external integration points associated with other brain entities.

The feature of functional portability (FP) arises due to the introduction of NLM. The execution of FP is introduced to prevent and limit overstimulation. In FP, the suitable external integration point from a brain entity experiences overstimulation executes the role of functional portability. A block diagram showing the implementation of NLM and FP is in Fig. 5. The relation in Fig. 5 considers that information integration comprises: (1) Logical Synapse Triggering and Formation (LSTF), (2) Integration Point Analysis, Identification and Selection (ITP),

(3) Communication and Context Initiation (CCI), and (4) Communication and Context Tear Down (CCT).

In Fig. 5, the synapse is a synthetic entity that is integrated into the biological system. The synthetic synapse enables communications in a desired manner between biological entities. The synthetic synapse is introduced to enable communications between different brain entities. The triggered synapse in the LSTF phase enables the activation of the functionality of the ITP, CCI, and CCT. In renal failure, the successful execution of the LSTF phase is followed by the ITP. The execution of the ITP leads to CCI initialization. The role of communication is the verification of the presence of a communication link between micro-brain (associated with the kidney) and the macro-brain.

A successful CCI execution after the successful activation of the synthetic synapse implies a re-activation of communications. The concerned communication is between the kidney's micro-brain and the macro-brain (conventional brain). In this case, kidney failure arises due to a breakdown of kidney regulatory mechanisms-brain communications. The FP functionality is also crucial. In the case where the CCI initialization is not successful, the failure arises due to high cognitive load in the kidney regulatory mechanisms-brain communication path. The execution of FP becomes important in this case. In FP, an alternative path in the biological system to enable micro-brain and macro-brain communications are utilized. Multiple alternative paths can also be used utilized within the biological system in this manner. The measurement of a path based cognitive load is required to determine the occurrence of high cognitive load. The cognitive load is determined by observing the number of integrated biological entities along a given path. A flow-chart showing the execution of the failure determination is in Fig. 6.

The essence of the presentation in Fig. 5, and the flow-chart in Fig. 6 is the description of the task associated with a consideration of the role of communication function execution. The role is being considered from the perspective of making additional observation prior to concluding on the causes of organ failure. In the approach being considered,

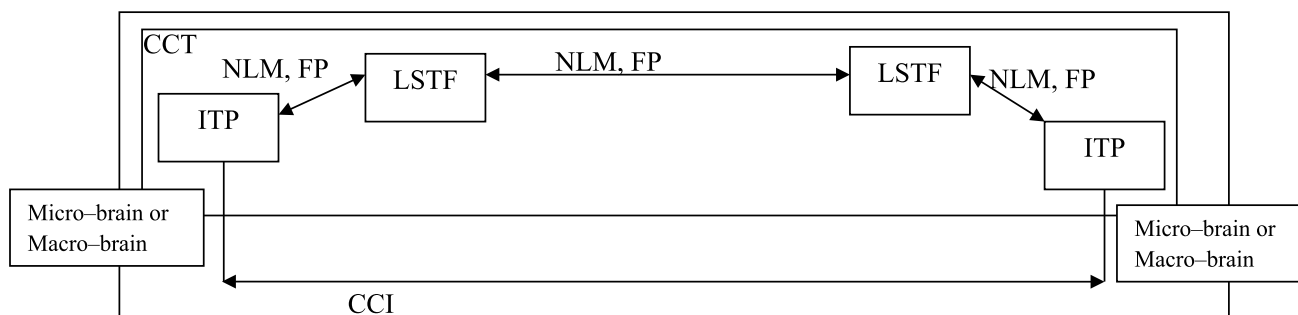


Fig. 5 Relations between micro-brain and macro-brain showing the LSTF, NLM, and FP

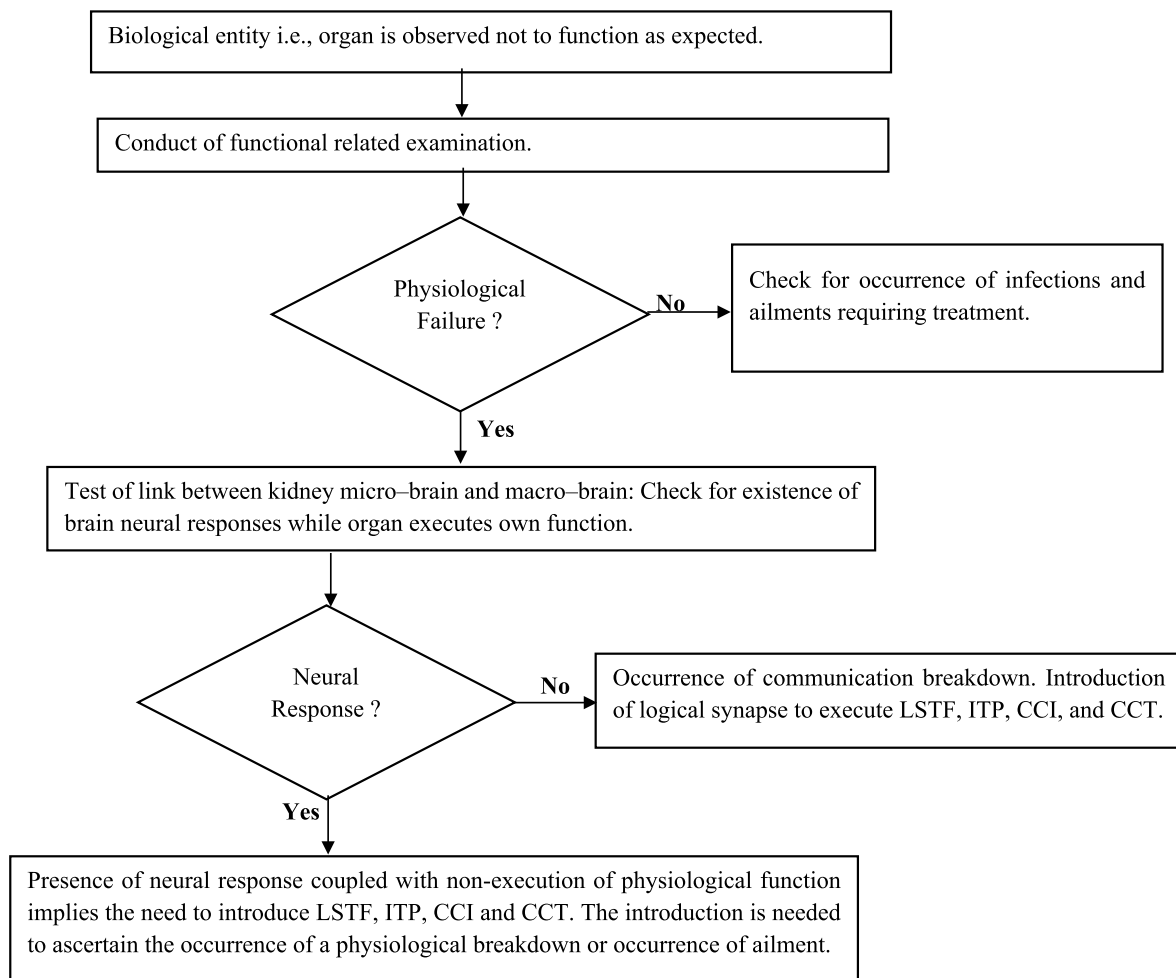


Fig. 6 Flowchart showing how biological entity relations necessitate using the LSTF, ITP, CCI, and CCT

the occurrence of organ failure is deemed due to the breakdown in the function of the physiological aspect and computational aspects. Existing physiological aspect failures can be investigated via existing clinician methods and organ function tests. However, similar approaches do not exist for the investigation of the functionality of the computational aspect via the occurrence of signal transduction i.e., signal communications. The focus of the discussion in the scenarios presented in Figs. 5 and 6 is on the entities and functionalities required to evaluate the functionality of the computational aspect. The functionality of the computational aspect is via the occurrence of successful signal communications.

An important aspect of the system relations in Fig. 5, and the flowchart in Fig. 6 is their implication in future systems development. The introduction of the macro-brain and micro-brain entities signify the presence of self-regulatory mechanisms in biological organs. This is the case with and without the consideration of the proposed approach. In Fig. 5, the LSTF phase definition describes the execution of functionalities by different physiological organs in

phases. The portability of functionality feature arising from the proposed FP, and the NLM entity arise from the introduction of novel electronic components. Such novel electronic components are feasible considering the advances in nano-medical robotics. The ITP functionality is also realized via the incorporation of nano-electronics that execute medical applications. In Fig. 5, the execution of functionalities within the context of the CCT involves the functionalities of the synthetic components. The synthetic components i.e., nano-electronics for medical applications enable the execution of communication context initialization and tear-up.

The scenario in Fig. 6 i.e., shows the flowchart for the relations associated with the execution of the procedures in the CCI, and CCT. In this case, the clinician methods and appropriate tests such as the kidney (renal) function test or liver function tests presents pathological results showing that an organ is not functional. In the case of the existing approach, the occurrence of physiological failure necessitates the execution of an organ transplant procedure or other temporal therapy approach. However, the inclusion of the

proposed approach considers the examination of the communication between the concerned organ and the brain. This involves micro-brain (identified organ communications), and macro-brain (identified main brain in the central nervous system). In Fig. 6, the activation of the corresponding brain region regulating the functioning of an organ is checked while the organ executes its expected functionality. The basis for this reasoning and assertion is that all organs have a brain region that regulates their functionality via regulatory mechanisms. For example, the functionality of the kidney and liver is regulated via the brain region of the hypothalamus. In the case where no hypothalamus neural response is observed to correlate with kidney or liver functionality, then a communication breakdown is deemed to have occurred. The verification of a communication breakdown provides another feasible cause for the occurrence of organ breakdown. This provides an alternative path for organ failure related therapy development.

4 Proposed Evolutionary Consciousness Paradigm (ECP)

In MMCP, an integration point can execute NLM and FP capabilities in the event of over-stimulation. Over-stimulation arises at an integration point when input stimuli strength exceeds the expected and defined input threshold. In addition, over-stimulation occurs when the integration point experiences a reduced ability to sustain its current level of input stimuli. Being robust, it is recognized that the human biological system has its own mechanisms to mitigate against sensory overload [31, 32].

However, a significant increase in the input stimuli at the integration point or a significant decrease in the integration point can occur. The concerned change can lead to unexpected changes incapable of being supported by the biological system. Sensory overload can be mitigated by enabling evolving integration point capacity. In this case, an integration point is a biological tissue that combines multiple input stimuli.

In the case where there is a significant change in the capacity of the integration point, integration point evolution becomes important. The proposed paradigm is the evolutionary consciousness paradigm (ECP). In the ECP, an integration point has a partition enabling weighted sensory input segregation and aggregation alongside multiple weighted integration points with sensory inputs. Let α be the set of integration points:

$$\alpha = \{\alpha_1, \alpha_2, \dots, \alpha_I\} \quad (1)$$

The integration point $\alpha_i, \alpha_i \in \alpha$ has multiple sub-channels such that:

$$\alpha_i = \{\alpha_i^1, \alpha_i^2, \dots, \alpha_i^M\} \quad (2)$$

The weight associated with the sub-input channel $\alpha_i^m, \alpha_i^m \in \alpha_i$ at the epoch $t_y, t_y \in t, t = \{t_1, \dots, t_Y\}$ is denoted $W_1(\alpha_i^m, t_y)$. The weight $W_1(\alpha_i^m, t_y)$ has a set of allowable values with the minimum and maximum being $W_1^{min}(\alpha_i^m, t_y)$, and $W_1^{max}(\alpha_i^m, t_y)$, respectively. The parameters $W_1^{min}(\alpha_i^m, t_y)$, and $W_1^{max}(\alpha_i^m, t_y)$ have defined input levels. The input levels associated with $W_1(\alpha_i^m, t_y)$, $W_1^{min}(\alpha_i^m, t_y)$ and $W_1^{max}(\alpha_i^m, t_y)$ are denoted $\beta_1(\alpha_i^m, t_y)$, $\beta_1^{min}(\alpha_i^m, t_y)$ and $\beta_1^{max}(\alpha_i^m, t_y)$, respectively. The output from the integration point α_i is denoted $\theta(\alpha_i)$ and given as:

$$\theta(\alpha_i) = \sum_{m=1}^M \sum_{y=1}^Y \beta_1(\alpha_i^m, t_y) W_1(\alpha_i^m, t_y) \quad (3)$$

Let $I_1(\alpha) \in \{0, 1\}, i \in \{1, 2, 3, \dots, I\}$ be the brain integration point indicator for interfaces in α . All the interfaces are and are not within either a micro-brain or macro-brain when $I_1(\alpha) = 0$ and $I_1(\alpha) = 1$, respectively. A challenge arises when the input is $\gamma_1(\alpha_i, t_y)$ such that the conditions $I_1(\alpha) = 1, \gamma_1(\alpha_i, t_y) > \beta_1^{max}(\alpha_i^m, t_y)$ or $I_1(\alpha) = 1, \gamma_1(\alpha_i, t_y) < \beta_1^{min}(\alpha_i^m, t_y)$ holds true. The occurrence of either of these conditions results in a case where interfaces are unable to process $\gamma_1(\alpha_i, t_y)$ because it is out of range. In this case, integration point evolution is deemed necessary.

Hence, the set of integration points, α also equals the integration point. Therefore, the set of un-evolved integration points is given as α . The set of evolved integration points associated with α is denoted ϑ . In this case, all relations and conditions defined for the set α are also applicable to ϑ . Hence, a re-representation of the conditions associated with evolved integration point ϑ is deemed unnecessary. Integration point evolution from α to ϑ is successful when $\vartheta_i, \vartheta_i \in \vartheta, I(\vartheta) = 1, \beta_1^{min}(\vartheta_i^m, t_y) \leq \gamma_1(\vartheta_i, t_y) \leq \beta_1^{max}(\vartheta_i^m, t_y)$ holds true. In this case, the conditions defined for α_i hold true for the evolved integration point in ϑ_i .

The transition from the un-evolved integration point to the evolved integration point is mediated via a reality check procedure. Each integration point and associated sub-interfaces correspond to a pre-determined and pre-configured response from the intelligent agent. The input and corresponding weight vectors are stored and the process of de-evolution is activated. The inputs and the corresponding weight factors are also stored, and evolution, as embodied in the proposed ECP, is activated.

The flowchart for ECP is presented in Fig. 7. In the flowchart, ECP functionality comprises two stages. These stages are the biological routing execution, and neural integration point editing. In biological routing execution, a biological route is sought that ensures the reduction of

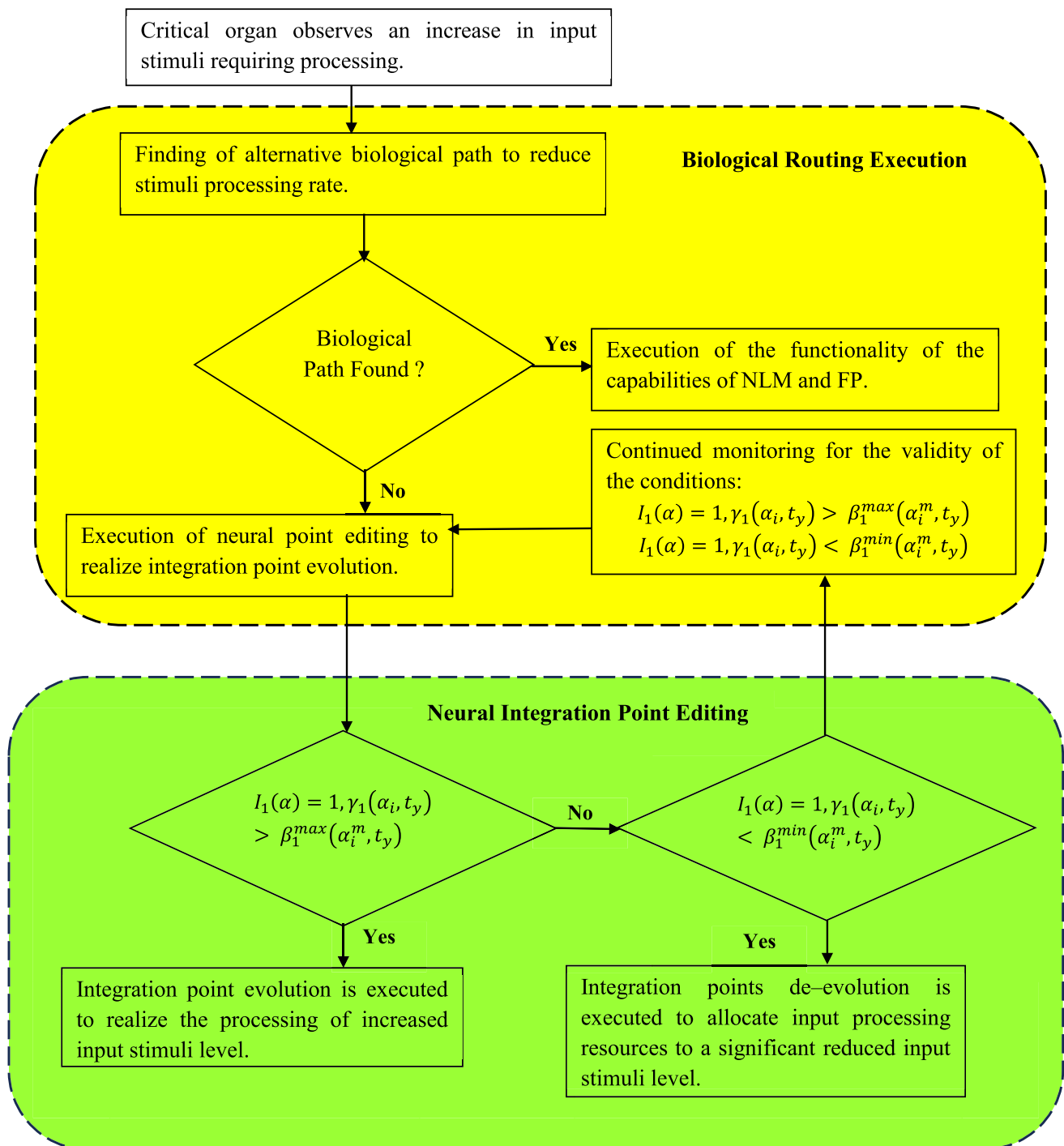


Fig. 7 Flowchart showing steps associated with the execution of neural integration point editing

input stimuli presented in a given time. The functionalities of NLM, and FP are executed when biological routes are found that enable a reduction of the input stimuli presented in a given time. In the case where no biological routes are found, the integration point evolution is executed via the use of neural editing. The execution of

neural editing is a key procedure in the neural integration point editing stage. In the neural integration point editing stage, conditions are further evaluated to determine the execution of either integration point evolution or integration point de-evolution.

5 Underlying Mathematical Framework

The discussion here presents the underlying mathematical framework for MMCP and ECP. The framework opines that communications in MMCP and ECP are executed by nerves next to the concerned organs. The communications require interaction between an equal number of nerves associated with the micro-brain and macro-brain. This is called the equality condition for communications in the nervous system. The perspective extends the integrated information theory (IIT) on the occurrence of information integration. The IIT is extended by Negro in [33] where the emergentist integrated information theory is presented.

The equality condition has been motivated from the perspective that a contact-based communication system requires an equal number of communication entities at the transmitter and receiver ends. In this case, the number of communication entities whose interaction constitutes the link is equal in this consideration. This is motivated by the necessity to have an equal number of interacting wire pairs in communication networks.

In the formulation, the communication entities and links are heterogeneous. The formulation considers that communication entities regardless of their state occupy a volume and have a communication related activity that is dynamic and observable. The nerve to neuron ratio is derivable from a given volume realizable via the aggregation of smaller volumes. This applies to neurons in the biological system in aspects concerning communications and the equality criterion. The evaluation of the number of communication entities is done considering the volumes associated with the nerve to neuron ratio dN_E , neurons dN_N , and change in time dt .

Negro in [33] recognizes that in IIT, the information context is internal and pertains to the system generating the information. The discussion in [33] recognizes that integrated information gives rise to the operation that is perceived as consciousness in each system. Negro [33] proposes a notion that integrated information seeds consciousness. This is because the emergentist IIT assumes that consciousness is achievable at an optimal spatio-temporal scale. It is also noted that integrated information can be used as a tool or supporting framework to proactively infer the state of consciousness. Therefore, it is important to have a framework enabling transiting between different states of consciousness. This transition should be done in a resource-efficient manner. In a biological context, this refers to the occurrence of evolution. MMCP and ECP enable the transition to a higher level of information integration. Such a notion arises from continuing evolution and increasing complexity in biological systems [34, 35]. The evolution and complexity embedded in MMCP

and ECP involve stable relations between heterogeneous biological entities. The notion of heterogeneity is observed as a rule for biological systems in [36].

The rest of the discussion describes the MMCP and ECP in the first part and second parts, respectively. Furthermore, perspectives on the validation of the model are presented in the third part. In addition, the performance formulation is presented in the fourth part.

5.1 MMCP: Underlying Theory

This aspect presents the underlying mathematical concept in MMCP. In MMCP, an aggregation of a significant number of nerve endings or neurons related structures tends to a brain like system. The brain like system describes the micro-brain which relates with the macro-brain via nerve ending structures or neurons related structures. The communication occurs between an equal number of nerves when:

$$\sum_{j=1}^Q \left(\iiint \prod_{p \in \{N_E^i, N_N^i\}} m_j(p, t_y) dN_E dN_N dt \right) = \sum_{j=1}^Q \left(\iiint \left(\prod_{p \in \{N_E^i, N_N^i\}} \alpha_j M_j(p, t_y) dN_E dN_N dt \right) \right) \quad (4)$$

In (4), the left-hand side and right-hand side are associated with the micro-brain and macro-brain, respectively. The micro-brain's nerve endings and neuronal assemblies occur in groups. The total number of groups is the upper limit of the summation operation in (4). Each of these groups has a function describing the number of neurons and the nerve to neuron ratio. For the Q th group, the function describing the number of neurons is denoted $m_j(p = N_N^i, t_y)$ at the instant t_y . In addition, the nerve to neuron ratio is $m_j(p = N_E^i, t_y)$, at the instant t_y .

In the macro-brain on the right-hand side in (4), the relations described also apply. In such a case, $m_j(p = N_N^i, t_y)$ and $m_j(p = N_E^i, t_y)$ are re-written as $M_j(p = N_N^i, t_y)$, and $M_j(p = N_E^i, t_y)$, respectively. The parameters $M_j(p = N_N^i, t_y)$, and $M_j(p = N_E^i, t_y)$ describe the nerve to neuron ratio and the number of neurons in the i th synaptic environment context at the epoch t_y , respectively. The notion of the i th synaptic context at the epoch t_y applies to the macro-brain functions $M_j(p = N_N^i, t_y)$, and $M_j(p = N_E^i, t_y)$. In addition, α_1, α_2 and α_Q is the proportion of the macro-brain's first group, second group and the Q th group's neural resources and structure that is directed toward the micro-brain system on the left-hand side of (4), respectively.

The validity of (4) implies that the total number of micro-brain (biological poly-computer)'s neural communication

equals that of the macro-brain (macro-brain)'s neural communication agents. The communication agents have a one-to-one linkage relation in the wired biological poly-computing communication networks. A non-one-to-one relation arises in the scenarios given as:

$$\sum_{j=1}^Q \left(\iiint \prod_{p \in \{N_E^i, N_N^i\}} m_j(p, t_y) dN_E N_N dt \right) > \sum_{j=1}^Q \left(\iiint \left(\prod_{p \in \{N_E^i, N_N^i\}} \alpha_j M_j(p, t_y) dN_E N_N dt \right) \right) \quad (5)$$

$$\sum_{j=1}^Q \left(\iiint \prod_{p \in \{N_E^i, N_N^i\}} m_j(p, t_y) dN_E N_N dt \right) < \sum_{j=1}^Q \left(\iiint \left(\prod_{p \in \{N_E^i, N_N^i\}} \alpha_j M_j(p, t_y) dN_E N_N dt \right) \right) \quad (6)$$

The scenario in (5) arises due to a decrease in the macro-brain's attention resources or neuron death (in a stage preceding neuron birth via neurogenesis). Another plausible cause for (5) is an increase in the value of $m_j(p = N_E^i, t_y) \times m_j(p = N_N^i, t_y)$, $j \in \{1, 2, \dots, Q\}$ associated with the micro-brain poly-computing node. A feasible approach enabling the realization of (5) is neuron seeding (artificial stimulation of neurogenesis).

The condition and scenario in (6) arise due to the increase in the macro-brain attentional resources i.e., variable α_j in (6) due to the path of the micro-brain poly-computer on the left-hand side of (6). In addition, the reduction in the integral on the left-hand side of (6) leads to the validity of (6). In the case where the heterogeneity of the synaptic environment context is considered, the relation in (4) can be rewritten as:

$$\sum_{j=1}^Q \sum_{i=1}^B \left(\iiint \prod_{p \in \{N_E^i, N_N^i\}} m_j(p, t_y) dN_E N_N dt \right) = \sum_{j=1}^Q \sum_{i=1}^B \left(\iiint \left(\prod_{p \in \{N_E^i, N_N^i\}} \alpha_j M_j(p, t_y) dN_E N_N dt \right) \right) \quad (7)$$

The formulation in (7) assumes that synaptic contexts occur as separate clusters. However, this is ideal and cluster coupling should be considered. The occurrence of this cluster coupling is denoted $c_j(p = N_E^i, t_y)$, and $C_j(p = N_N^i, t_y)$ for the nerve to neuron ratio and the neuron in the i th synaptic environment for the micro-brain at the epoch t_y , respectively. The nerve to neuron ratio and the neuron cluster coupling for the macro-brain in the i th synaptic environment for the macro-brain at the epoch t_y are denoted $C_j(p = N_E^i, t_y)$, and $C_j(p = N_N^i, t_y)$, respectively. The consideration of cluster

coupling in the synaptic environment extends the equality condition to a non-one-to-one case. The equality condition associated with the occurrence of nerves driving the communication in MMCP is re-stated considering cluster coupling as:

$$\sum_{j=1}^Q \sum_{i=1}^B \left(\iiint \prod_{p \in \{N_E^i, N_N^i\}} c_j(p, t_y) m_j(p, t_y) dN_E N_N dt \right) = \sum_{j=1}^Q \sum_{i=1}^B \left(\iiint \left(\prod_{p \in \{N_E^i, N_N^i\}} \alpha_j C_j(p, t_y) M_j(p, t_y) dN_E N_N dt \right) \right) \quad (8)$$

In our consideration of the micro-brain (in kidney) and macro-brain (the brain in the central nervous system), the kidney shares identity with linking nerves in the parasympathetic nervous system. The consideration also applies to other organs linked to the brain via the parasympathetic nervous system. The MMCP posits that each organ driven by the parasympathetic nervous system communicates in a manner that can be described by the equality criterion. The effect of the parasympathetic nervous system is modelled by the inter-biological entity coupling factor. The coupling factor associated with $c_j(p, t_y)$, $p \in \{N_E^i, N_N^i\}$, and $C_j(p, t_y)$, $p \in \{N_E^i, N_N^i\}$ are $\gamma_j^1(p, t_y)$, $p \in \{N_E^i, N_N^i\}$, and $\gamma_j^2(p, t_y)$, $p \in \{N_E^i, N_N^i\}$ respectively. The equality condition can be given as:

$$\sum_{j=1}^Q \sum_{i=1}^B \left(\iiint \prod_{p \in \{N_E^i, N_N^i\}} c_j(p, t_y) m_j(p, t_y) \gamma_j^1(p, t_y) dN_E N_N dt \right) = \sum_{j=1}^Q \sum_{i=1}^B \left(\iiint \left(\prod_{p \in \{N_E^i, N_N^i\}} \alpha_j C_j(p, t_y) M_j(p, t_y) \gamma_j^2(p, t_y) dN_E N_N dt \right) \right) \quad (9)$$

The functions $m_j(p, t_y)$, $p \in \{N_E^i, N_N^i\}$ are not necessarily positive and may be negative at some epochs. The product $\left(\prod_{p \in \{N_E^i, N_N^i\}} m_j(p, t_y) \right)$ has the property and behaviour given as:

$$\iiint \left(\prod_{p \in \{N_E^i, N_N^i\}} m_j(p, t_y) dN_E N_N dt \right) \neq 0 \quad (10)$$

$$\iiint \left(\prod_{p \in \{N_E^i, N_N^i\}} m_j(p, t_y) dN_E N_N dt \right) < 0 \quad (11)$$

$$\iiint \left(\prod_{p \in \{N_E^i, N_N^i\}} m_j(p, t_y) dN_E N_N dt \right) > 0 \quad (12)$$

$$m_j(N_E^i, t_y) > 0, m_j(N_N^i, t_y) > 0, m_j(N_E^i, t_y) < 0, m_j(N_N^i, t_y) < 0 \quad (13)$$

$$m_j(p, t_1) \neq m_j(p, t_2) \neq \dots m_j(p, t_Y), p \in \{N_E^i, N_N^i\}, t \in \{t_1, \dots, t_Y\} \quad (14)$$

$$\iiint \left(\prod_{p \in \{N_E^i, N_N^i\}} M_j(p, t_y) dN_E N_N dt \right) \neq 0 \quad (15)$$

$$\iiint \left(\prod_{p \in \{N_E^i, N_N^i\}} \alpha_q M_j(p, t_y) dN_E N_N dt \right) < 0, q \in \{1, \dots, Q\} \quad (16)$$

$$\iiint \left(\prod_{p \in \{N_E^i, N_N^i\}} \alpha_q M_j(p, t_y) dN_E N_N dt \right) > 0, q \in \{1, \dots, Q\} \quad (17)$$

$$m_j(N_E^i, t_y) > 0, m_j(N_N^i, t_y) > 0, m_j(N_E^i, t_y) < 0, m_j(N_N^i, t_y) < 0 \quad (18)$$

$$M_j(p, t_1) \neq M_j(p, t_2) \neq \dots M_j(p, t_Y), p \in \{N_E^i, N_N^i\}, t \in \{t_1, \dots, t_Y\} \quad (19)$$

The function described by the evaluation of $\iiint \left(\prod_{p \in \{N_E^i, N_N^i\}} m_j(p, t_y) dN_E N_N dt \right)$ are co-minimum and co-maximum over all time instants.

5.2 ECP: Underlying Mathematical Theory

The equality condition is important in describing the underlying mathematical approach for the proposed ECP. In this case, the biological evolution is deemed to affect the coupling incidence, neurogenesis, and projection in an independent manner. A similar evolutionary path is deemed to influence the biological system integration point system. An integration point evolution is deemed necessary when:

$$\sum_{j=1}^Q \sum_{i=1}^B \left(\iiint \prod_{p \in \{N_E^i, N_N^i\}} c_j(p, t_y) m_j(p, t_y) dN_E N_N dt \right) \rightarrow \infty \quad (20)$$

$$\sum_{j=1}^Q \sum_{i=1}^B \left(\iiint \prod_{p \in \{N_E^i, N_N^i\}} C_j(p, t_y) M_j(p, t_y) dN_E N_N dt \right) \rightarrow \infty \quad (21)$$

The relations in (20) and (21) are associated with the micro-brain and macro-brain, respectively. Both describe cases where there is a significant increase in the number of biological communication agents. The increase leads

to over-stimulation. The integration point in both cases is deemed overwhelmed since its nerve bearing capacity is not infinite. The set of biological integration points associated with the micro-brain and macro-brain are ζ_m and ζ_M , respectively.

$$\zeta_m = \{\zeta_m^1, \zeta_m^2, \zeta_m^3, \dots, \zeta_m^K\} \quad (22)$$

$$\zeta_M = \{\zeta_M^1, \zeta_M^2, \zeta_M^3, \dots, \zeta_M^L\} \quad (23)$$

The evolved integration point associated with ζ_m and ζ_M are denoted as φ_m and φ_M , respectively.

$$\varphi_m = \{\varphi_m^1, \varphi_m^2, \varphi_m^3, \dots, \varphi_m^S\} \quad (24)$$

$$\varphi_M = \{\varphi_M^1, \varphi_M^2, \varphi_M^3, \dots, \varphi_M^V\} \quad (25)$$

An integration point evolution to use φ_m is required when:

$$\begin{aligned} & \sum_{j=1}^Q \sum_{i=1}^B \left(\iiint \prod_{p \in \{N_E^i, N_N^i\}} c_j(p, t_y) m_j(p, t_y) dN_E N_N dt \right) \\ & \gg \sum_{k=1}^K N_C(\zeta_m^k, t_y), \zeta_m^k \epsilon \zeta_m \end{aligned} \quad (26)$$

$N_C(\zeta_m^k, t_y), \zeta_m^k \epsilon \zeta_m$ is the nerve bearing capacity of the k th micro-brain integration point, at the epoch t_y .

The integration point evolution to use φ_M is required when:

$$\begin{aligned} & \sum_{j=1}^Q \sum_{i=1}^B \left(\iiint \prod_{p \in \{N_E^i, N_N^i\}} C_j(p, t_y) M_j(p, t_y) dN_E N_N dt \right) \\ & \gg \sum_{v=1}^V N_C(\zeta_M^v, t_y), \zeta_M^v \epsilon \zeta_M \end{aligned} \quad (27)$$

$N_C(\zeta_M^v, t_y), \zeta_M^v \epsilon \zeta_M$ is the nerve bearing capacity of the v th macro-brain integration point, at the epoch t_y .

ECP incorporation leads to new scenarios for the micro-brain and macro-brain described as:

$$\begin{aligned} & \sum_{j=1}^Q \sum_{i=1}^B \left(\iiint \prod_{p \in \{N_E^i, N_N^i\}} c_j(p, t_y) m_j(p, t_y) dN_E N_N dt \right) \\ & \approx \sum_{k=1}^K \sum_{s=1}^S \prod_{d \in \{\zeta_m^k, \varphi_m^s\}} N_C(d, t_y), \zeta_m^k \epsilon \zeta_m, \varphi_m^s \epsilon \varphi_m \end{aligned} \quad (28)$$

$$\sum_{j=1}^Q \sum_{i=1}^B \left(\iiint \prod_{p \in \{N_E^i, N_N^i\}} C_j(p, t_y) M_j(p, t_y) dN_E N_N dt \right) \approx \sum_{l=1}^L \sum_{v=1}^V \prod_{f \in \{\zeta_M^l, \varphi_M^v\}} N_C(f, t_y), \zeta_M^l \in \zeta_M, \varphi_M^v \in \varphi_M \quad (29)$$

The influence of $\gamma_j^1(p, t_y), p \in \{N_E^i, N_N^i\}$, and $\gamma_j^2(p, t_y), p \in \{N_E^i, N_N^i\}$ is incorporated in (28) and (29) to yield:

$$\sum_{j=1}^Q \sum_{i=1}^B \left(\iiint \prod_{p \in \{N_E^i, N_N^i\}} c_j(p, t_y) m_j(p, t_y) \gamma_j^1(p, t_y) dN_E N_N dt \right) \approx \sum_{k=1}^K \sum_{s=1}^S \left(\prod_{d \in \{\zeta_m^k, \varphi_m^s\}} N_C(d, t_y) \right), \zeta_m^k \in \zeta_m, \varphi_m^s \in \varphi_m \quad (30)$$

$$\sum_{j=1}^Q \sum_{i=1}^B \left(\iiint \prod_{p \in \{N_E^i, N_N^i\}} C_j(p, t_y) M_j(p, t_y) \gamma_j^2(p, t_y) dN_E N_N dt \right) \approx \sum_{l=1}^L \sum_{v=1}^V \left(\prod_{f \in \{\zeta_M^l, \varphi_M^v\}} N_C(f, t_y) \right), \zeta_M^l \in \zeta_M, \varphi_M^v \in \varphi_M \quad (31)$$

5.3 Perspectives on Validation

The presented research focuses on developing a communications and computing perspective of the biological system. The proposed perspective presents the view that communications between different biological entities can be re-triggered to mitigate against the notion of the occurrence of organ failure. The implied communications are executed in the network enabling different organs to communicate with the brain. The description of the proposed perspective and approach identifies relations between different parameters.

The concerned parameters are related to (1) Biological integration points, (2) Integration point evolution and (3) Communication entities. The biological integration point related parameters are the number of (1) Organ specific integration points, (2) Organ specific integration point sub-channels, (3) The number of inputs per integration point sub-channel. Each integration point sub-channel has associated weight with an assigned value. The evolution related parameters are the number of: (1) unevolved, (2) evolved, and (3) synthetic integration points. The communication entities related parameter is the number of nerves.

In the research associated with the description of computing and communication systems, performance modeling and simulation related results are presented. As an example, the research in [37] is a suitable example. However, the conduct of simulation and evaluation of performance benefits is

challenging in this case. The challenge arises because of the non-availability of the aforementioned parameters which are the envisaged outputs of a non-invasive comprehensive neuroimaging procedure.

5.4 Performance Modelling

The performance formulation considers a set of biological entities denoted as α_b such that:

$$\alpha_b = \{\alpha_b^1, \alpha_b^2, \dots, \alpha_b^J\} \quad (32)$$

In addition, let $I_F(\alpha_b^j, t_y) \in \{0, 1\}$, $\alpha_b^j \in \alpha_b$ denote the functional status of the j th biological entity α_b^j at the epoch t_y . The j th biological entity α_b^j is functional and non-functional at the epoch t_y when $I_F(\alpha_b^j, t_y) = 0$, and $I_F(\alpha_b^j, t_y) = 1$, respectively. Furthermore, the biological entity α_b^j has the physiological aspect, $\alpha_b^{j,p}$ and the computational aspect, $\alpha_b^{j,c}$. Each of the physiological aspect and computational aspects has a functional duration denoted as $\gamma(\alpha_b^{j,p}, t_y)$, and $\gamma(\alpha_b^{j,c}, t_y)$, respectively. The functional status of the physiological aspect and computational aspect is presented as $I_F(m, t_y) \in \{0, 1\}$, $m \in \{\alpha_b^{j,p}, \alpha_b^{j,c}\}$. The entity m is functional and non-functional at the epoch t_y when $I_F(m, t_y) = 1$, and $I_F(m, t_y) = 0$, respectively. The operational duration of the biological entity is an important metric that describes the effectiveness of the biological entity in executing its intended functionalities. Hence, the operational duration is identified as an important performance criterion. The operational duration of the biological entity in the existing case, and proposed case are denoted Γ_1 , and Γ_2 , respectively.

$$\Gamma_1 = \sum_{p=1}^P \sum_{y=1}^Y \gamma(\alpha_b^{j,p}, t_y) I_F(\alpha_b^{j,p}, t_y) \quad (33)$$

$$\Gamma_2 = \sum_{p=1}^P \sum_{c=1}^C \sum_{y=1}^Y \left(\gamma(\alpha_b^{j,p}, t_y) I_F(\alpha_b^{j,p}, t_y) + \gamma(\alpha_b^{j,c}, t_y) I_F(\alpha_b^{j,c}, t_y) \right) \quad (34)$$

The overall operational duration of the concerned biological organism is formulated considering multiple biological entities. In this case, the concerned operational duration in the existing case, and proposed case are denoted Γ_3 , and Γ_4 , respectively.

$$\Gamma_3 = \sum_{j=1}^J \sum_{p=1}^P \sum_{y=1}^Y \left(\gamma(\alpha_b^{j,p}, t_y) I_F(\alpha_b^{j,p}, t_y) \right) \quad (35)$$

$$\Gamma_4 = \sum_{j=1}^J \sum_{p=1}^P \sum_{c=1}^C \sum_{y=1}^Y \left(\gamma(\alpha_b^{j,p}, t_y) I_F(\alpha_b^{j,p}, t_y) + \gamma(\alpha_b^{j,c}, t_y) I_F(\alpha_b^{j,c}, t_y) \right) \quad (36)$$

The computational aspect associated with the incorporation of the proposed mechanism is realized via the use of nano-electronics, and sub nano-electronics. Hence, it is crucial to consider their operational efficiency when integrated into native biological systems. However, operational efficiency has not been considered in (34), and (36). The operational efficiency of the entity $\alpha_b^{j,c}$ at the epoch t_y is denoted as $\beta(\alpha_b^{j,c}, t_y)$. Given a consideration of the operational efficiency, the biological entity, and biological organism operation duration is denoted as Γ_5 , and Γ_6 , respectively.

$$\Gamma_5 = \sum_{p=1}^P \sum_{c=1}^C \sum_{y=1}^Y \left(\gamma(\alpha_b^{j,p}, t_y) I_F(\alpha_b^{j,p}, t_y) + \gamma(\alpha_b^{j,c}, t_y) \beta(\alpha_b^{j,c}, t_y) I_F(\alpha_b^{j,c}, t_y) \right) \quad (37)$$

$$\Gamma_6 = \sum_{j=1}^J \sum_{p=1}^P \sum_{c=1}^C \sum_{y=1}^Y \left(\gamma(\alpha_b^{j,p}, t_y) I_F(\alpha_b^{j,p}, t_y) + \gamma(\alpha_b^{j,c}, t_y) \beta(\alpha_b^{j,c}, t_y) I_F(\alpha_b^{j,c}, t_y) \right) \quad (38)$$

Table 1 Performance evaluation and simulation parameters

S/N	Parameter	Value
1	Number of biological entities—physiological aspect	30
2	Number of biological entities—computational aspect	30
3	Minimum functional status—physiological aspect	0.39%
4	Mean functional status—physiological aspect	54.30%
5	Maximum functional status—physiological aspect	96.30%
6	Minimum functional status—computational aspect	0.78%
7	Mean functional status—computational aspect	37.42%
8	Maximum functional status—computational aspect	98.25%
9	Minimum operational duration—physiological aspect	2.299 h
10	Mean operational duration—physiological aspect	31.419 h
11	Maximum operational duration—physiological aspect	64.2470 h
12	Minimum operational duration—computational aspect	5.112 h
13	Mean operational duration—computational aspect	35.783 h
14	Maximum operational duration—computational aspect	62.316 h
15	Minimum efficiency—computational aspect	1.16%
16	Mean efficiency—computational aspect	41.87%
17	Maximum efficiency—computational aspect	87.58%

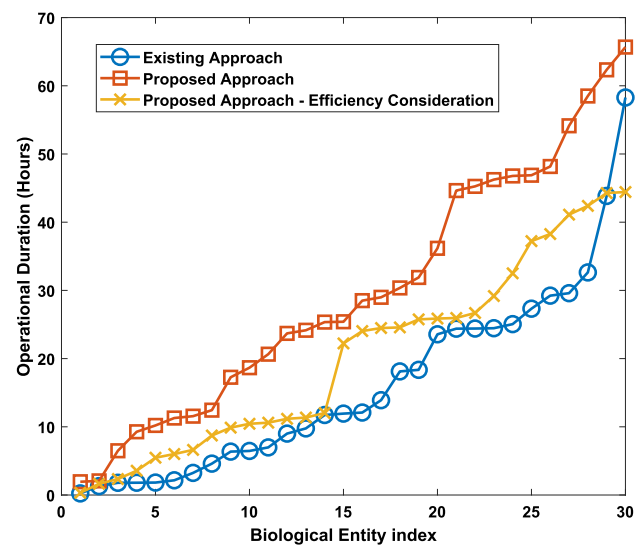


Fig. 8 Operational duration related results obtained in the performance evaluation via simulation

6 Performance Evaluation and Simulation

The performance evaluation results obtained via simulation are presented in this section. The considered scenario is one in which the biological organism comprises multiple organs. In the biological scenario, successive organs execute an increasing number of physiological functions. Each organ has a varying operational duration. In addition, the functional status is not considered in binary form i.e.,

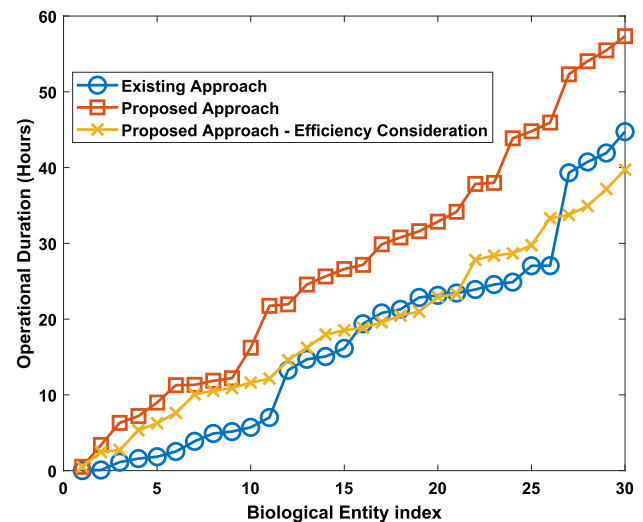


Fig. 9 Operational duration related results obtained in the performance evaluation via simulation. In this case, the computational aspect has a duration that is one-half (1/2) of the operational duration of the physiological aspect for the concerned organ

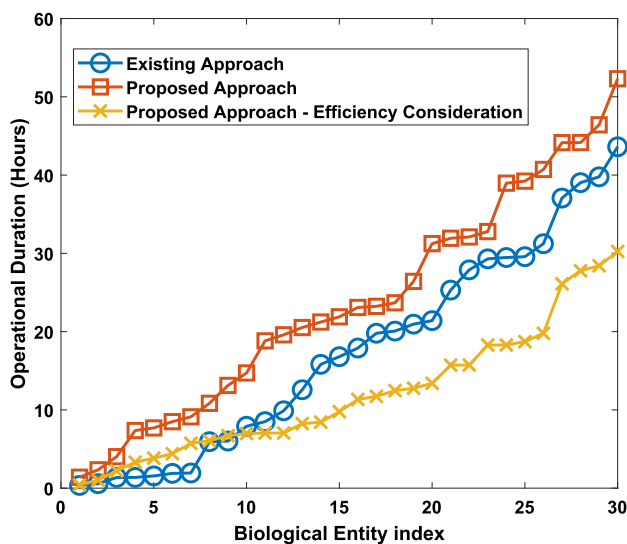


Fig. 10 Operational Duration related results obtained in the Performance Evaluation via simulation. In this case, the computational aspect has a duration that is one-third ($1/3$) of the operational duration of the physiological aspect of the concerned organ

values of 1 and 0. Instead, the functional status has values ranging between 0 and 1. In this case, a value of 0 indicates total organ collapse and failure while a value of 1 indicates excellent organ functioning. The performance simulation parameters used to investigate the operational duration as the main performance metric is shown in Table 1. The performance evaluation results obtained via simulation are shown in Fig. 8.

The results in Fig. 8 shows that the use of the proposed approach enhances the operational duration for the concerned biological system. In addition, it can be seen that the consideration of the operational efficiency for the introduced synthetic i.e., nano-electronic components still enhances the operational duration. Further analysis of the results obtained via numerical evaluation shows that the use of the proposed approach (without considering the efficiency) instead of the existing approach enhances the operational duration by an average of 54.1%. The use of the proposed approach (considering the efficiency) instead of the existing approach enhances the operational duration by an average of 27.4%. Given that the proposed approach is being used, the performance is observed to reduce by an average of 36.8% when the effect of inefficiencies is considered.

In addition, the performance evaluation also considers the case where the computational aspect associated with the proposed approach has a significantly reduced operational duration. The simulation considers the case where the computational aspect has an operational duration is half i.e., ($1/2$), and one—third ($1/3$) of the operational duration of the physiological aspect. The results associated with the

case where the computational aspect has a duration that is ($1/2$) are presented in Fig. 9. In the case of Fig. 9, the use of the proposed solution (without consideration of efficiency) instead of the existing solution enhances the operational duration by an average of 48.7%.

Furthermore, the use of the proposed solution (with consideration of efficiency) instead of the existing solution enhances the operational duration by an average of 25.2%. In addition, the consideration of the arising inefficiencies degrades the operational duration by an average of 29.4%. The performance evaluation associated results for the case of the one-third ($1/3$) consideration shows that the use of the proposed approach (with efficiency consideration) results in reduced operational duration in comparison to the existing case. In this case, the results are presented in Fig. 10. In this case, the use of the proposed approach instead of the existing approach enhances the operational duration by an average of 38.4%.

7 Conclusion

The discussion presents evolutionary perspectives on consciousness in relation to an intelligent agent. Intelligent agents in this context are biological entities and non-biological entities. The micro-brain macro- brain consciousness paradigm (MMCP) and the evolutionary consciousness paradigm (ECP) have been proposed. MMCP and ECP are set in the context of providing a framework to understand how consciousness emerges in intelligent entities without solely relying on the occurrence of multi-sensory fusion as proposed in the integrated information theory. The presented research proposes the incorporation of advanced nano-electronics for signal transduction pathway monitoring and adaptation. The signal transduction in this case has the autonomous capacity to ensure the resolution of communication related failures prior to deciding on organ failure. Performance evaluation shows that the use of the proposed approach enhances the operational duration of the biological entity comprising multiple organs by an average of 25.2% to 54.1%.

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