A Hypothesis of Distributed Fungal Intelligence and Planetary-Scale Cognition

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Abstract

Fungal mycelia form extensive, adaptive networks that integrate local chemical, electrical, hydraulic, and mechanical information across changing environments. Their capacity for signal propagation, resource redistribution, behavioral plasticity, and persistent network reconfiguration raises a carefully bounded question: might some large fungal systems exhibit forms of distributed information processing that are not well captured by organism-centered models of cognition? This hypothesis does not attribute human-like consciousness, language, intention, or extraterrestrial communication to fungi. Rather, it proposes a research program for examining whether mycelial networks display measurable properties associated with distributed computation: stimulus-specific signaling, temporal integration, memory-like changes in later responses, adaptive routing, and collective decision dynamics.

The framework treats fungal intelligence as a graded and embodied possibility, expressed at time scales and through substrates very different from those of animal nervous systems. Apparent slowness is therefore not, by itself, evidence of informational simplicity; network function should be assessed relative to fungal physiology, geometry, energy use, and ecological context. Candidate experiments include field-scale observation of ancient mature networks, repeated-stimulus protocols, multichannel electrophysiological and chemical recording, controlled resource-allocation challenges, and preregistered analyses that distinguish robust response patterns from environmental confounds.

The larger value of this work is methodological as well as biological. It invites a sapiential—wisdom-oriented—approach to cognition: one that asks how sensing, memory, coordination, and adaptation may arise in living systems without presuming a brain, a face, or human temporal scale. Even negative results would sharpen the boundaries between sophisticated distributed physiology and cognition.

Positive results would expand the empirical study of intelligence beyond familiar animal models while preserving scientific restraint.

Keywords: mycelium; fungal signaling; distributed cognition; bioelectricity; collective behavior; ecological intelligence; planetary-scale inquiry

1. The Limits of Neurocentric Models of Cognition

Scientific understanding of cognition has historically been shaped by the nervous systems of animals and, particularly, by the human brain. Consequently, characteristics such as rapid electrical transmission, specialized neurons, centralized processing, sensory integration, memory, and behavioral response have become familiar reference points for identifying cognitive activity. These characteristics provide powerful models for understanding animal intelligence, but they may not define the only biological architecture capable of acquiring, integrating, retaining, and responding to information.

Increasing attention is therefore being directed toward cognition in organisms that possess no neurons or centralized nervous system. Bacteria, unicellular eukaryotes, plants, and fungi can sense environmental conditions, modify their behavior in response to changing circumstances, allocate resources, and retain effects of previous states or exposures. Whether such processes should formally be described as cognition remains debated. Nevertheless, their existence raises an important methodological question: if cognition is defined too closely by the mechanisms through which animals accomplish it, biologically different forms of information processing may be overlooked.

Fungi present an especially interesting case. A filamentous fungus develops as a branching network of hyphae that can extend through a heterogeneous environment while continually sensing local conditions, redistributing resources, modifying growth, and responding to disturbance. Electrical activity has been recorded in fungal systems, although its biological functions, mechanisms of propagation, and significance for long-distance coordination remain incompletely understood. The highly modular and spatially distributed architecture of mycelium further complicates direct comparison with conventional neuronal systems.

This architectural difference also introduces a temporal problem. Neural cognition is commonly associated with signaling occurring over milliseconds to seconds, whereas fungal physiological and electrical processes may operate much more slowly. Slow signaling, however, should not automatically be interpreted as evidence of limited information-processing capacity. The meaningful timescale of information integration may depend upon the physical dimensions, network architecture, signaling mechanisms, metabolic requirements, and ecological functions of the system performing it.

A sessile biological network extending through soil, wood, or an ecosystem faces very different informational problems from those faced by a mobile animal requiring immediate sensory and motor

responses. Its significant environmental changes may develop over minutes, hours, seasons, or longer periods. Consequently, the appropriate question may not be whether a mycelial network processes information as rapidly as an animal brain, but whether it integrates information at a rate appropriate to its own spatial organization and biological requirements.

We therefore propose that fungal information processing be examined without assuming that neuronal organization, centralized control, or animal rates of signal propagation constitute necessary conditions for cognition. This does not require attributing consciousness, subjective experience, or intelligence to fungi. It requires only that the informational capabilities of mycelial networks be evaluated according to experimentally measurable properties of the networks themselves.

Such an approach permits a more precise question to be asked: What degree of information acquisition, integration, retention, and coordinated response can occur within a spatially distributed living network in the absence of a nervous system?

That question provides the starting point for the present hypothesis.

2. Mycelial Networks as Distributed Biological Systems

The vegetative body of a filamentous fungus differs fundamentally from the body plan of most animals. Rather than concentrating sensory, processing, and transport functions within specialized organs, a fungus develops through an expanding network of microscopic filaments known as hyphae. These hyphae branch, reconnect through fusion, penetrate heterogeneous substrates, and collectively form the mycelium. The resulting organism is therefore not simply an aggregation of fungal threads, but a dynamic biological network whose architecture changes continuously in response to its environment. (Fricker et al., 2017; Simonin et al., 2012)

This network organization provides fungi with an unusual combination of decentralization and integration. Individual regions of a mycelium encounter local conditions—nutrients, moisture, temperature, competing organisms, physical barriers, and damage—while remaining functionally connected to other portions of the organism. Resources acquired in one region can be transported toward metabolically active regions elsewhere, permitting the network to exploit environments in which resources are unevenly distributed in space and time. Growth itself becomes a form of environmental exploration. (Heaton et al., 2010; Fricker et al., 2017)

The architecture of the network is not fixed. Hyphae may proliferate in favorable regions, reduce investment in depleted areas, reinforce pathways between resource-rich locations, or redirect growth toward newly encountered resources. Experiments with cord-forming and wood-decay fungi have demonstrated extensive reorganization of network structure following changes in resource availability. Such plasticity suggests that the state of one region of the mycelium can influence developmental and

resource-allocation processes occurring elsewhere in the network. (Fukasawa et al., 2020; Fukasawa & Ishii, 2023; Heaton et al., 2012)

This distinction is important for the present hypothesis. A distributed information-processing system need not possess a single anatomical location corresponding to a brain. Information integration could instead emerge through interactions among many semi-autonomous components whose local activities collectively alter the state and future behavior of the larger network. In such a system, architecture itself may participate in information processing: changes in connectivity, transport capacity, growth direction, and resource allocation may embody previous environmental interactions and influence subsequent responses.

Mycelial networks therefore present characteristics familiar from other complex adaptive networks. They are decentralized, redundant, dynamically reconfigurable, capable of transporting materials across spatially separated regions, and able to maintain function despite localized damage. Branching and reconnection provide alternative pathways through which resources—and potentially signals—may propagate. At the same time, continual remodeling allows the network to balance competing requirements of exploration, transport efficiency, resilience, and metabolic cost.

These properties should not, by themselves, be interpreted as evidence of cognition. Network optimization and adaptive morphology can arise through biochemical and developmental mechanisms without subjective awareness or centralized decision-making. Nevertheless, they demonstrate that the fungal organism already performs a prerequisite operation for any proposed distributed information-processing system: it coordinates activities among spatially separated components while continually modifying its organization in response to environmental conditions.

The scale of this organization is particularly significant. At the microscopic level, individual hyphal tips encounter and respond to highly localized conditions. At larger scales, interconnected hyphae form transport and signaling pathways extending through the substrate. At still larger ecological scales, fungal networks interact with plant roots, microorganisms, competing fungi, and changing physical conditions. Information relevant to survival is therefore generated at multiple spatial scales and potentially over multiple temporal scales.

This multiscale organization raises a central question. When a distant portion of a mycelium encounters a new resource, suffers injury, or experiences environmental stress, by what mechanisms does that information influence the remainder of the organism? Chemical gradients, cytoplasmic transport, hydraulic processes, developmental regulation, and electrical phenomena may all contribute. No single mechanism should be assumed in advance to account for the coordinated behavior of the network.

Accordingly, we propose treating the mycelium first as a measurable distributed biological system rather than assigning it a cognitive label. Its topology can be mapped; resource flows can be traced; electrical and chemical activity can be recorded; environmental stimuli can be experimentally controlled; and changes occurring at increasing distances from the point of stimulation can be measured. This approach permits the degree of functional integration within the network to become an experimental question.

The crucial transition is therefore from observing that a fungus forms a network to determining whether, and to what extent, that network integrates information.

If reproducible evidence demonstrates that localized environmental events produce structured, coordinated, and history-dependent responses across spatially separated regions of a mycelium, the question of fungal cognition becomes considerably more precise. Rather than asking whether a fungus possesses something analogous to a brain, we can ask whether the network itself performs some of the integrative functions for which brains represent only one biological solution.

3. Electrical and Chemical Signaling in Fungi

If a mycelial network functions as an integrated biological system, some mechanism must permit conditions encountered in one region to influence activity elsewhere. Material transport, chemical signaling, hydraulic processes, ion fluxes, and changes in membrane potential provide several possible mechanisms. Of particular interest is the growing evidence that fungi exhibit measurable electrical activity whose relationship to network-wide coordination remains incompletely understood. (Buffi et al., 2025)

Electrical phenomena are not unique to nervous systems. All living cells maintain electrochemical gradients across their membranes, and changes in ion distribution can alter membrane potential and cellular behavior. In fungi, proton pumps and ion channels involving calcium, potassium, chloride, and other ions contribute to membrane polarization, growth, environmental sensing, and physiological regulation. Calcium signaling is especially important in fungal growth, development, stress response, and cellular communication. (Itani et al., 2023)

Early electrophysiological studies identified electrical currents associated with fungal hyphal tips and reported transient changes in membrane potential resembling, in certain respects, action potentials found in other organisms. More recent experiments using extracellular electrodes have detected spontaneous fluctuations and spike-like events in fungal mycelia and fruiting bodies. These electrical patterns may occur across markedly different timescales, ranging from relatively rapid events to oscillations lasting many minutes or hours. (Adamatzky, 2022; Buffi et al., 2025)

The resemblance between some fungal electrical events and neuronal action potentials should nevertheless be treated cautiously. Similarity of waveform does not establish similarity of biological

function. Electrical fluctuations may accompany growth, ion transport, metabolism, nutrient translocation, mechanical disturbance, or other physiological processes without representing information-bearing signals in the sense ordinarily associated with nervous systems. Furthermore, measurements from fungal tissues are technically difficult and vulnerable to environmental noise, electrode effects, movement, hydration changes, and other experimental artifacts. (Blatt et al., 2024; Buffi et al., 2025)

This uncertainty is scientifically valuable. The important question is not whether fungal electrical activity can immediately be interpreted as a language, but whether particular electrical events reliably correspond to particular biological conditions and whether those events propagate through the network in ways that influence subsequent activity elsewhere.

A signal becomes especially interesting when three properties can be demonstrated: it is reproducibly associated with an identifiable stimulus or internal state; it propagates beyond the immediate site at which that condition occurs; and its arrival elsewhere produces or predicts a measurable change in the receiving region. Demonstrating these properties would move the investigation from the observation of electrical fluctuation toward evidence for biological information transfer.

Chemical signaling provides a complementary mechanism. Changes in nutrient availability, pH, water status, metabolites, signaling molecules, and extracellular compounds can alter fungal growth and physiology. Calcium-dependent pathways and other intracellular signaling systems translate environmental conditions into changes in cellular activity. Electrical and chemical signaling should therefore not necessarily be regarded as competing explanations. They may constitute interacting components of a larger electrochemical communication system.

This possibility becomes particularly significant in a continuous branching organism. A local stimulus might initially alter ion concentrations or membrane potential, initiate biochemical signaling cascades, modify cytoplasmic or nutrient flow, and ultimately change growth or metabolic activity at another location. Information could therefore be represented not by a single electrical pulse but by a coordinated pattern involving electrical, chemical, metabolic, and morphological changes distributed through time and space.

Such a system would differ fundamentally from conventional digital communication. Information need not be represented as discrete symbols or binary states. It could instead reside in changes of frequency, amplitude, duration, interval, spatial propagation, synchronization, or combinations of several physiological variables. The relevant unit of information might therefore be a temporal or spatial pattern rather than an isolated electrical event.

This distinction also cautions against premature attempts to translate fungal electrical spikes directly into human linguistic units. Reports of apparently structured electrical spiking in fungi are provocative, but claims that these patterns constitute words or language remain controversial. Before semantic content can reasonably be proposed, it must first be established that recorded patterns arise biologically, respond systematically to controlled stimuli, propagate through living networks, and produce reproducible downstream effects. (Adamatzky, 2022; Blatt et al., 2024)

For the present hypothesis, therefore, the existence of a fungal “language” need not be assumed. A more fundamental experimental question precedes it:

Does a mycelial network generate distinguishable internal signal patterns corresponding to distinguishable environmental events or physiological states?

If the answer is yes, a second question follows:

Can those patterns be transmitted through the network, retained or modified by previous experience, and recognized through reproducible responses elsewhere in the organism?

Only after these questions are addressed does it become scientifically meaningful to ask whether fungal signaling possesses anything analogous to syntax, representation, or communication.

The immediate objective is consequently not to decode a fungal language, but to determine whether there is anything systematic to decode.

4. Cognition Without Neurons

The concept of cognition presents an unusual difficulty in biology because there is no universally accepted boundary separating cognitive processes from complex adaptive physiology. In animals, cognition is ordinarily associated with nervous systems and may encompass perception, learning, memory, decision-making, problem-solving, and the integration of information across sensory and behavioral domains. When similar functional properties appear in organisms without neurons, however, their interpretation becomes considerably more controversial.

This disagreement partly reflects differences in definition. If cognition is defined anatomically as information processing performed by nervous systems, an organism without neurons cannot be cognitive by definition. If cognition is instead defined functionally—as the acquisition, integration, retention, and use of information in ways that modify subsequent behavior—then the question becomes empirical rather than anatomical. Under this second definition, the mechanisms by which information is processed may differ radically among biological systems. (Šekrst, 2026)

The history of neuroscience itself provides reason for caution about equating cognition exclusively with neuronal signaling. Glial cells were once regarded primarily as structural and metabolic support for neurons. Astrocytes are now recognized as active participants in synaptic regulation, learning, memory, and network dynamics. Unlike neurons, astrocytes do not communicate principally through rapid sequences of conventional action potentials. Their activity involves complex intracellular calcium dynamics, biochemical signaling, metabolic interactions, and communication with neurons and other glial cells across multiple spatial and temporal scales. (Escalada et al., 2024)

This development does not imply that fungal cells and astrocytes are functionally equivalent, nor that calcium signaling constitutes evidence of consciousness. The comparison is valuable for a different reason. It demonstrates that biologically important information processing can occur through mechanisms that differ substantially from the rapid electrical signaling historically emphasized in neuronal models.

Calcium provides an especially instructive example. Ca^{2+} is an evolutionarily ancient and widely conserved intracellular signaling molecule. In fungi, transient changes in cytosolic calcium participate in environmental sensing and regulate processes including polarized growth, development, reproduction, stress responses, and adaptation. Calcium channels, pumps, exchangers, binding proteins, and downstream signaling pathways allow changes in cellular conditions to be translated into coordinated physiological responses.

The presence of calcium signaling in both fungal and nervous systems should not be interpreted as evidence that the systems perform equivalent computations. Rather, it demonstrates that evolution repeatedly employs dynamic electrochemical states to encode and regulate biological responses. The relevant scientific question is therefore not whether fungal signaling resembles neuronal signaling closely enough to qualify as cognition, but whether fungal networks exhibit functional properties ordinarily associated with information processing.

Several such properties can be stated without invoking consciousness. A system may detect differences in its environment; discriminate among stimuli; alter its response according to previous exposure; integrate information arriving from different locations; select among alternative physiological or developmental responses; retain state-dependent changes over time; and coordinate activity among spatially separated components. Each of these properties can, in principle, be experimentally measured.

This functional approach also helps distinguish cognition from consciousness. The two terms should not be treated as interchangeable. A biological system might demonstrate sophisticated information processing, learning, memory, or adaptive decision-making without providing evidence of subjective experience. The present hypothesis therefore does not require a claim that fungi are conscious. Indeed,

introducing consciousness prematurely would make the hypothesis more difficult to evaluate experimentally.

Instead, we propose a graded approach. Rather than asking whether a fungus either “has” or “does not have” cognition, investigators can measure particular capacities individually. Does the network discriminate between stimuli? Does previous exposure alter later responses? Can information originating in one region influence responses in another? Does the network retain effects of prior events after the original stimulus has disappeared? Does disruption of particular pathways alter subsequent network-wide behavior? Do repeated stimuli produce habituation, sensitization, or other history-dependent changes?

Such questions transform a philosophical dispute into an experimental program.

They also shift attention from individual fungal cells to the organization of the network. Cognitive properties, if present, need not reside within any single hypha. They could emerge from interactions among large numbers of connected components, just as many properties of complex biological systems arise from collective dynamics that are not attributable to any individual element in isolation.

This possibility is particularly relevant to mycelium because the organism continuously changes its own physical architecture. Growth alters connectivity. Fusion creates new pathways. Damage removes pathways. Resource availability changes transport patterns. Previous environmental conditions can therefore become physically incorporated into the subsequent state of the network. In this limited but experimentally meaningful sense, network architecture itself may constitute a form of biological memory: the present organization of the system contains consequences of its past.

We must nevertheless distinguish such structural memory from cognitive memory in animals. A remodeled fungal network does not necessarily “remember” an event in the subjective sense. But if previous conditions produce persistent changes that systematically influence later responses, the network possesses a history-dependent state. Determining how much information such states contain, how long they persist, and whether they affect responses to future conditions becomes experimentally tractable.

The same reasoning applies to decision-making. A growing fungal network encountering several possible resource pathways does not need consciously to “choose” among them for its behavior to be studied in decision-theoretic terms. If different environmental inputs are integrated and consistently produce alternative patterns of growth or resource allocation, the underlying mechanisms can be characterized without anthropomorphic assumptions.

We therefore suggest that the question of fungal cognition initially be decomposed into measurable component processes: sensing, discrimination, integration, retention, adaptation, selection, and

coordinated response. Only after these properties have been characterized should broader cognitive terminology be evaluated.

This approach provides an important safeguard for the hypothesis. Evidence for one component must not automatically be treated as evidence for all others. Electrical signaling does not demonstrate memory. Memory-like behavior does not demonstrate consciousness. Network coordination does not demonstrate intention. Each proposed capability requires its own experimental evidence.

At the same time, the reverse inference should also be avoided. The absence of neurons does not demonstrate the absence of biologically meaningful information processing.

The central question therefore becomes increasingly specific:

Can a mycelial network integrate information across its distributed structure, retain consequences of previous states, and use that information to modify subsequent responses?

If it can, the important scientific problem will no longer be whether the system sufficiently resembles an animal brain. It will be to determine what kind of information-processing system a mycelial network actually is.

5. The Spatial–Temporal Scale Hypothesis

The speed at which a biological system processes information is commonly evaluated against the familiar timescales of animal nervous systems. Neural signals can propagate rapidly, sensory events may be discriminated within milliseconds, and motor responses often occur within fractions of a second. Such speeds are indispensable to organisms that must navigate rapidly changing environments, pursue prey, avoid predators, and coordinate movement. They need not, however, constitute a universal temporal standard for biological information processing.

Different organisms inhabit substantially different temporal regimes. Sensory systems vary in their ability to resolve rapidly changing stimuli, while metabolic rate, body size, environmental conditions, and behavioral ecology influence the characteristic rates at which organisms interact with their surroundings. A temporal interval that is behaviorally significant to one organism may therefore be relatively insignificant to another.

This observation suggests a broader principle: the characteristic timescale of information processing should be evaluated in relation to the spatial scale, architecture, signaling mechanisms, and functional requirements of the system performing it.

The principle is especially relevant to distributed biological networks. As the spatial dimensions of a network increase, signals may require progressively longer intervals to propagate between distant

regions. If the system's relevant environmental processes also unfold slowly, however, increased transmission time does not necessarily prevent effective integration. What appears slow when compared with neuronal transmission may be entirely adequate relative to the ecological processes upon which the organism depends.

Mycelial networks provide a useful system in which to examine this relationship experimentally. Their spatial extent can range from microscopic colonies to interconnected networks occupying substantial areas of substrate. Signals and resources moving through such systems encounter distances vastly greater than those separating neighboring cells. At the same time, many environmental variables relevant to fungal survival—resource depletion, substrate colonization, moisture changes, competition, seasonal cycles, plant growth, and decomposition—develop over minutes, hours, days, months, or longer.

Consequently, the functional significance of a fungal signal cannot be determined from propagation velocity alone. A signal requiring minutes or hours to influence a distant region might appear extraordinarily slow relative to a neuronal impulse while remaining rapid relative to the ecological event to which the network is responding.

This leads us to propose the Spatial–Temporal Scale Hypothesis:

The capacity of a distributed biological network to integrate information depends not upon absolute signaling speed alone, but upon the relationship among signaling velocity, network dimensions, persistence of information, network topology, and the characteristic timescale of the processes to which the system responds.

This formulation produces experimentally testable consequences. Increasing the distance between a stimulus and a monitored region should alter response latency in a measurable manner if information is propagating through the network. Different pathways through the same network may produce different latencies. Highly connected regions may permit faster or more reliable propagation than sparsely connected regions. Damage to connecting pathways should alter or eliminate particular responses. Repeated measurements should reveal whether propagation rates remain stable or vary according to physiological state.

More importantly, signal propagation must be compared with information persistence. A distributed system cannot integrate a slowly propagating signal if the relevant information disappears before distant regions can respond to it. Conversely, a slowly changing network may successfully integrate information if physiological states persist long enough for signals originating in different locations to interact.

Integration time may therefore be as important as transmission speed.

This distinction is familiar in other areas of biology. Cellular signaling networks frequently integrate biochemical events occurring over seconds, minutes, or hours. Developmental systems integrate molecular signals over still longer periods. Circadian systems organize physiology around approximately daily cycles, while seasonal and developmental processes can retain and respond to information over months or years. Biological information processing already occupies a hierarchy of timescales.

The mycelial network may similarly possess more than one characteristic temporal scale. Rapid local responses could coexist with slower regional coordination, while still slower processes could influence network architecture, resource distribution, reproductive activity, or long-term adaptation. Electrical oscillations reported in fungi at different characteristic frequencies are consistent with the possibility that fungal physiology cannot adequately be described by a single processing rate.

This multiscale possibility changes the experimental question. Instead of asking simply, “How fast does a fungus signal?”, we should ask:

“At what spatial scales, over what temporal intervals, and through which mechanisms does information remain capable of influencing the state of the network?”

Answering that question requires experiments designed across both space and time. Electrodes positioned at increasing distances from a controlled stimulus could measure propagation and attenuation. Simultaneous recordings from multiple regions could determine whether distant activity becomes synchronized or otherwise statistically related. Repeated stimuli could establish whether prior network states influence subsequent propagation. Environmental perturbations could test whether different classes of stimulus generate distinguishable spatial-temporal signatures.

Crucially, randomized and physically disconnected controls would be necessary to distinguish genuine network propagation from environmental correlations or instrumental artifacts. The hypothesis predicts not merely that distant regions will fluctuate together, but that relationships among stimulus location, network topology, propagation delay, signal pattern, and downstream response will exhibit reproducible structure.

Such experiments could also establish the limits of integration. There may be distances beyond which coordination becomes negligible, timescales over which signals lose biological significance, or network configurations incapable of maintaining coherent responses. Negative results would therefore be informative. The Spatial–Temporal Scale Hypothesis does not predict unlimited integration; it predicts that the relevant limits can be measured.

This point becomes particularly important when considering very large biological networks. It would be unjustified to infer that increasing spatial extent automatically produces increasing cognition. Larger

networks impose greater communication delays, energetic costs, noise, and problems of coordination. Scale may create new integrative possibilities, but it may equally create constraints.

The hypothesis therefore makes no necessary claim about planetary consciousness. It establishes a prerequisite question that must be answered before such a possibility can be meaningfully discussed: Can distributed biological information remain integrated as the spatial and temporal dimensions of the network increase?

If the answer proves to be yes over progressively larger scales, then the apparent slowness of fungal signaling acquires a different interpretation. It may represent neither a defective approximation of neuronal communication nor an obstacle to complex organization, but a mode of information processing adapted to a biological system whose dimensions and environmental relationships differ fundamentally from our own.

From this perspective, “fast” and “slow” cease to be absolute descriptions of cognitive capability. They become relationships between an information-processing system and the world to which it must respond.

6. Distributed Information Integration in Large Mycelial Networks

Signal transmission alone does not establish distributed cognition. A biological network may convey chemical, electrical, hydraulic, or metabolic changes over considerable distances without combining those signals into an integrated representation or coordinated response. The critical question is therefore not simply whether information travels through a mycelium, but whether information originating at different locations interacts in ways that modify the subsequent state and behavior of the network.

This distinction separates communication from integration.

Consider a mycelial network exposed simultaneously to several environmental conditions. One region may encounter a new nutrient source, another declining moisture, a third physical damage, and a fourth chemical signals associated with a competitor or symbiotic organism. An integrated system would not necessarily respond to these events as independent local processes. Information concerning one condition could alter the network’s response to another, producing a coordinated outcome dependent upon their combined occurrence.

Such behavior can be experimentally distinguished from simple signal propagation. If stimulus A produces response A′ and stimulus B produces response B′, simultaneous presentation of A and B can be compared with the mathematical combination expected from the two isolated responses. If the resulting network state consistently contains properties not predictable from the independent

responses, this would provide evidence of nonlinear interaction and potentially of information integration.

The location at which such integration occurs is an open question.

One possibility is that mycelial networks contain functionally important integration hubs. Highly interconnected regions, dense zones of hyphal fusion, metabolically active junctions, or persistent transport nodes could receive signals from multiple network regions and disproportionately influence subsequent activity. Such structures would not necessarily constitute a brain or nervous center. They would instead represent network locations whose topology or physiology gives them an unusually important role in coordinating distributed activity.

A second possibility is that no unique integration center exists. Information may instead be represented by the collective state of the network itself. Electrical potentials, calcium dynamics, chemical gradients, metabolic activity, resource flows, oscillatory relationships, and network topology could interact across many locations, allowing integration to emerge from distributed processes rather than convergence upon a single anatomical structure.

These alternatives produce different experimental predictions.

If integration depends strongly upon a limited number of hubs, selective disruption of those regions should disproportionately impair coordinated network responses. Damage to peripheral regions should have smaller effects. Network mapping should reveal locations whose connectivity or physiological activity predicts their functional importance.

If integration is highly distributed, the consequences of localized disruption should be different. Coordinated responses may remain relatively robust following removal or isolation of individual regions and deteriorate progressively as connectivity is reduced. Information represented across multiple pathways could therefore exhibit a degree of redundancy and resilience not expected from a system dependent upon a single processing center.

The distinction need not be absolute. Biological networks frequently combine local specialization with distributed organization. A mycelium could contain transient or semi-stable hubs while simultaneously retaining information across broader patterns of network activity. Moreover, the functional importance of particular regions could change as the organism grows, encounters new resources, suffers damage, or reorganizes its transport architecture.

This possibility introduces another important consideration: the integration architecture itself may be dynamic.

Unlike the relatively stable gross anatomy of an animal nervous system, a mycelial network continually constructs and removes portions of its own information-processing substrate. New hyphal branches create pathways. Anastomosis creates additional connections. Senescence removes them. Damage forces rerouting. Nutrient availability alters transport priorities. Consequently, the physical structure through which information travels is simultaneously a record of previous environmental interaction and an evolving component of future responses.

Information may therefore be represented at several levels simultaneously. A transient electrical event may encode an immediate local condition. A slower chemical or metabolic change may modify responsiveness over minutes or hours. Persistent alterations in connectivity may influence network behavior over much longer periods. The informational state of the organism could consequently be distributed not only across space but across multiple temporal layers.

This concept connects directly with the Spatial–Temporal Scale Hypothesis. If different forms of information persist for different durations, then rapidly propagating signals could interact with slowly changing physiological states and still slower architectural modifications. Integration need not require all components of the network to change simultaneously. It may instead depend upon the interaction of processes whose characteristic timescales differ substantially.

Detecting such integration will require simultaneous measurements from many regions rather than isolated electrode recordings. Multichannel electrophysiology could be combined with imaging, chemical measurements, resource tracing, and quantitative mapping of network architecture. Controlled stimuli could then be introduced at defined locations while responses are recorded across the system.

The resulting data should be analyzed not merely for individual spikes but for relationships among signals. Relevant variables may include amplitude, frequency, duration, propagation delay, phase relationships, synchronization, spatial sequence, recurrence, and changes in network connectivity. If information is represented through distributed patterns, examination of isolated events may conceal precisely the organization being sought.

This point has an important methodological implication. Human investigators naturally search for discrete signals because discrete signals are comparatively easy to recognize and classify. Yet a distributed biological network may encode information relationally. The meaningful variable could be a changing pattern among many simultaneous signals rather than any individual event.

The appropriate analytical tools may therefore include network theory, time-series analysis, information theory, nonlinear dynamics, and multivariate pattern recognition. Machine-learning methods could

assist in determining whether particular environmental conditions produce reproducible network states without requiring investigators to specify beforehand what those states should look like.

Such analysis must nevertheless be protected against overinterpretation. Complex datasets almost inevitably contain apparent patterns. Classification accuracy should therefore be evaluated against randomized controls, blinded trials, physically disconnected networks, environmental controls, and entirely novel datasets withheld from model training. A computational system that can distinguish experimental conditions only after extensive fitting to a particular dataset has not necessarily discovered biological communication.

A stronger result would occur if a model trained on one set of mycelial responses could correctly identify previously unseen stimuli from network activity alone. Stronger still would be evidence that the identified network pattern predicts a subsequent physiological or developmental response.

This leads to a practical operational definition of information integration for the present hypothesis:

A mycelial network demonstrates functional information integration when signals or states originating from spatially separated regions interact reproducibly such that the resulting network response contains predictive information not obtainable from the isolated local responses alone.

This definition deliberately avoids claims concerning consciousness or subjective experience. It gives us something measurable.

It also permits us to ask whether integration is centralized, distributed, hierarchical, transient, or some combination of these architectures. Rather than searching immediately for a fungal equivalent of a brain, we can map where and how information becomes functionally combined.

The possibility of distributed representation invites comparison with other biological and physical information systems, including distributed memory in neural networks. More speculative analogies to holographic representation may eventually prove heuristically useful, particularly if information is found to be robustly distributed across overlapping network states. Such analogies, however, should not be mistaken for evidence of a literal holographic mechanism. The first task is to establish experimentally whether distributed representation exists at all.

The decisive question is therefore no longer simply:

Does the mycelium transmit information?

It is:

Can the network combine information from different places and different times into a coherent state that alters what the organism subsequently does?

If such integration can be demonstrated reproducibly, then the mycelium would warrant consideration not merely as a signaling network, but as a distributed biological information-processing system.

7. Experimental Tests and Falsifiable Predictions

The hypothesis that large mycelial networks function as distributed information-processing systems is scientifically useful only if it generates observations capable of supporting, modifying, or rejecting it. Electrical activity, network complexity, adaptive growth, and long-distance resource transport are individually insufficient to establish information integration. Experiments must therefore distinguish coordinated information processing from ordinary physiological response, environmental correlation, and measurement artifact.

We propose a progressive experimental program in which increasingly demanding tests are applied to living mycelial networks. The objective is not initially to demonstrate intelligence, language, or consciousness, but to determine whether controlled information introduced at one or more locations can be detected, propagated, integrated, retained, and subsequently used elsewhere in the network.

7.1 Field-Scale Experimental Platform

The primary experimental platform should be an ancient, mature, ecologically continuous mycelial system studied in the field, rather than a small laboratory culture alone. A suitable candidate, subject to land-manager approval, site verification, ecological consultation, and all necessary permits, would be a large Oregon Armillaria colony or another comparably mature, well-characterized fungal network. The central question is whether a persistent network with substantial age and spatial extent exhibits reproducible information-processing signatures across multiple spatial and temporal scales. Smaller controlled cultures remain important for calibrating instruments and testing particular mechanisms, but they should support rather than substitute for the field-scale investigation. (Ferguson et al., 2003)

The field system should be observed through distributed, non-destructive sensing deployed at multiple locations within the mapped study area. Measurements may include extracellular electrical potentials, soil and substrate temperature, moisture, pH, oxygen, hydraulic conditions, chemical indicators, local growth or metabolic proxies, and relevant plant or microbial observations. Repeated baseline monitoring must precede any intervention so that normal daily, seasonal, weather-related, and state-dependent variation can be characterized. Network architecture and substrate continuity should be mapped as far as feasible, because apparent signal propagation cannot be interpreted independently of the routes through which biological, hydrological, or environmental influence may travel.

After a sufficient baseline period, carefully limited and ecologically appropriate stimuli may be introduced at several spatially separated locations under randomized schedules. The protocol should

include sham procedures, matched comparison sites, repeated trials across time, and records of weather, soil heterogeneity, hydrology, seasonal change, plant interactions, microbial activity, and equipment drift. The aim is not to prove intelligence, language, consciousness, extraterrestrial communication, or any cosmological interpretation. It is to determine whether a very large, old, persistent biological network displays reproducible propagation, integration, persistence, discrimination, or state-dependent response patterns that cannot be adequately explained by ordinary local physiology or unmeasured environmental correlation.

7.2 Establishing Stimulus–Response Specificity

The first requirement is to determine whether controlled stimuli produce reproducible network responses.

Spatially localized stimuli could include changes in nutrient availability, moisture, temperature, illumination where biologically relevant, mechanical disturbance, physical injury, or carefully selected chemical cues. Each stimulus should be presented repeatedly under standardized conditions while electrical, chemical, metabolic, and morphological responses are recorded at increasing distances from the point of application.

The central prediction is straightforward:

If mycelial activity carries information about environmental conditions, different classes of stimulus should produce statistically distinguishable patterns of network response beyond the immediate region of stimulation.

Failure to distinguish stimulus classes reproducibly would substantially weaken stronger claims of information encoding.

7.3 Demonstrating Propagation

A local physiological reaction is not equivalent to network communication. The next experiment must therefore establish whether stimulus-associated changes propagate through biologically connected portions of the mycelium.

Recording sites should be positioned at known distances and along mapped network pathways. Response latency, amplitude, duration, frequency characteristics, and attenuation should be measured as functions of distance and topology.

If a biological signal propagates through the network, response timing should exhibit reproducible relationships to distance and connectivity. Severing or blocking suspected pathways should alter those relationships.

Physically disconnected but environmentally adjacent fungal cultures provide an essential control. If apparently coordinated responses persist unchanged after biological connectivity has been eliminated, environmental coupling or instrumental artifacts must be considered before network transmission is inferred.

7.4 Testing Information Integration

The strongest early test of the present hypothesis involves multiple simultaneous stimuli.

Stimulus A and stimulus B should first be presented separately and their network responses characterized. The two stimuli should then be presented simultaneously at spatially separated locations.

Three outcomes are possible.

If the combined response is adequately predicted by the independent responses to A and B, there is little evidence for integration beyond parallel signal propagation.

If one signal consistently suppresses or modifies the other, interaction is occurring.

If simultaneous stimulation generates a reproducible network state containing properties not predictable from either stimulus alone or their simple combination, stronger evidence for information integration would exist.

This experiment should be extended to different stimulus combinations, spatial separations, and temporal intervals. Of particular interest would be whether the order in which stimuli occur changes the resulting network state.

7.5 Testing Network Memory

A distributed information-processing system may retain consequences of previous events.

Networks should therefore be exposed repeatedly to a standardized stimulus and later tested after intervals ranging from minutes to days or longer, depending upon the organism and response measured. Investigators should determine whether previous exposure alters response magnitude, latency, propagation pattern, growth behavior, or subsequent sensitivity.

Habituation-like reductions, sensitization-like increases, persistent pathway changes, or altered responses to previously encountered conditions would constitute forms of history dependence.

The critical control is an otherwise comparable network without the prior exposure.

If prior experience permits prediction of later network behavior after the initiating condition has disappeared, then the system possesses a measurable retained state. Whether that state should ultimately be called memory is a secondary terminological question.

7.6 Locating—or Failing to Locate—an Integration Nexus

The architecture of information integration can be investigated through selective disruption.

Network analysis may identify highly connected regions, major transport cords, dense zones of hyphal fusion, or physiologically active junctions. Candidate hubs can then be selectively isolated or severed while network-wide responses are monitored.

If disruption of a small number of particular regions repeatedly abolishes integrated responses while comparable peripheral disruption does not, this would support a hub-dependent architecture.

If integrated responses remain robust following localized disruption and deteriorate gradually as connectivity is progressively reduced, the result would favor a more distributed architecture.

A mixed result is also possible. Mycelial information processing may involve temporary or hierarchical hubs embedded within a broadly distributed network.

7.7 Testing Spatial–Temporal Scaling

The Spatial–Temporal Scale Hypothesis predicts measurable relationships among network dimensions, signaling velocity, topology, persistence, and response time.

Experiments should therefore be repeated across networks of different sizes and ages. Response latency and reliability should be measured as the distance between stimulation and recording locations increases.

If information integration has a finite spatial range, coordinated responses should eventually weaken or disappear as network dimensions exceed that range.

If larger networks compensate through altered topology, persistent signaling states, or hierarchical organization, characteristic response patterns may change rather than simply deteriorate.

The objective is not to demonstrate unlimited integration. It is to determine experimentally where the limits lie.

7.8 Pattern-Based Information

Individual electrical spikes may not constitute the relevant informational unit. Controlled experiments should therefore analyze entire spatial-temporal patterns.

Multichannel recordings can be examined for frequency structure, amplitude relationships, propagation sequences, phase relationships, synchronization, recurrence, and changes in network topology.

Machine-learning classifiers may then be trained on a subset of recordings to determine whether network states predict the stimulus that produced them.

The decisive test must involve previously unseen data.

If a classifier trained on one experimental series can identify stimulus classes from new network recordings at rates substantially exceeding chance, the network activity contains reproducible information about those stimuli.

A stronger result would occur if the identified pattern also predicts the organism's subsequent physiological or developmental response.

7.9 Structured Pattern Perturbation

Once reproducible endogenous patterns have been identified, a more demanding experiment becomes possible.

A naturally occurring electrical or temporal pattern associated with a known network state could be characterized mathematically and then reproduced experimentally as a controlled electrical perturbation applied to another region of the network or, with appropriate controls, to another comparable network.

The response to the original pattern should then be compared with responses to stimuli matched in overall energy, amplitude, and duration but having randomized temporal organization.

If the network responds differently and reproducibly to the structured pattern than to randomized controls, temporal organization itself would appear to carry biological significance.

This experiment provides a rigorous route toward investigating what might eventually be described as signal recognition without presupposing language, semantics, or intention.

7.10 Cross-Network Generalization

An especially important test would determine whether patterns discovered in one individual network generalize to others of the same species.

If stimulus-associated patterns are entirely idiosyncratic, they may reflect the particular architecture or physiological history of each organism.

If reproducible features appear across independently grown networks, stronger evidence would exist for species-characteristic signaling mechanisms.

Cross-species comparisons could later determine whether any informational structures are conserved or whether different fungal lineages employ fundamentally different signaling strategies.

7.11 Blinding, Randomization, and Negative Controls

The unconventional nature of the hypothesis requires unusually rigorous controls.

Stimulus presentation should be randomized wherever possible. Investigators analyzing recordings should be blinded to stimulus condition. Sham stimulation should be included. Dead substrate and disconnected biological networks should be monitored for environmental and instrumental artifacts. Electrical stimulation experiments should control for heating, electrolysis, electrode polarization, and nonspecific tissue damage.

Data-processing procedures should be defined before experimental conditions are revealed whenever feasible. Statistical thresholds and exclusion criteria should be established prospectively.

Machine-learning analyses should employ strict separation of training, validation, and test datasets to prevent overfitting.

Replication by independent laboratories would ultimately be essential.

7.12 Criteria That Would Weaken the Hypothesis

The present hypothesis should be reconsidered if controlled experiments consistently demonstrate that:

electrical and physiological fluctuations cannot reliably distinguish among environmental conditions;

apparent long-distance coordination disappears when environmental and instrumental correlations are adequately controlled;

responses at distant locations show no reproducible relationship to biological connectivity or network topology;

combined stimuli produce no interactions beyond independent local responses;

previous exposure produces no persistent or reproducible influence upon subsequent network behavior;

selective disruption reveals no evidence of either localized or distributed functional integration;

and pattern-classification results fail to generalize to blinded, previously unseen data.

Such findings would indicate that the observed complexity of fungal activity can be explained adequately by local physiological processes without invoking network-level information integration.

7.13 Criteria That Would Strengthen the Hypothesis

Conversely, evidence would accumulate if independent experiments demonstrate that:

distinct stimuli produce reproducibly distinguishable network states;

those states propagate according to biological connectivity;

information from spatially separated stimuli interacts nonlinearly;

previous events systematically modify later responses;

network disruption alters information integration in predictable ways;

spatial-temporal patterns generalize across repeated experiments;

and experimentally reproduced structured patterns elicit responses different from appropriately randomized controls.

No single finding would establish fungal intelligence or consciousness.

Taken together, however, such results would support a more limited and scientifically consequential conclusion:

A mycelial network can acquire, transmit, integrate, retain, and respond to information as a distributed biological system.

That proposition is experimentally falsifiable.

Only if it survives such tests should the larger implications be considered.

8. Speculative Extensions: Ecosystem and Planetary-Scale Organization

The preceding sections have developed a hypothesis that is, in principle, experimentally testable: mycelial networks may function as distributed biological information-processing systems capable of acquiring, transmitting, integrating, retaining, and responding to information across spatially separated regions. The discussion that follows extends beyond that evidentiary foundation. Its purpose is not to assert the existence of ecosystem or planetary consciousness, but to consider what larger questions would become scientifically meaningful if distributed information integration were demonstrated experimentally in fungal networks.

8.1 From Organism to Ecosystem

A mycelial network does not exist in biological isolation. In natural environments, fungi interact continuously with plants, bacteria, other fungi, animals, water, minerals, atmospheric conditions, and changing resource distributions. Mycorrhizal fungi form associations with plant roots, while decomposer fungi alter the chemical and physical environment through the breakdown and redistribution of organic matter. Fungal activity is therefore embedded within larger ecological networks containing numerous interacting biological and physical components.

If information processing occurs within an individual mycelial network, a subsequent question arises: to what extent can information cross the functional boundaries between organisms?

This question should initially be framed conservatively. Transfer of nutrients, signaling molecules, metabolites, or stress-related changes among interacting organisms does not demonstrate ecosystem cognition. Nevertheless, if the state of one organism systematically alters information processing in another, coordinated ecological behavior may emerge from interactions among multiple distributed networks.

The relevant unit of analysis could therefore expand gradually: from hypha, to mycelium, to fungal–plant association, to interacting community, and eventually to ecosystem.

At each transition, however, evidence for integration must be demonstrated rather than assumed.

8.2 Scaling and the Problem of Boundaries

The concept of an individual becomes increasingly difficult to define in distributed biological systems. A fungal colony may contain genetically related and interconnected regions extending across heterogeneous environments. Mycorrhizal associations connect fungi physically and chemically with plant roots. Plants themselves interact with microbial communities above and below ground. Ecological systems consequently contain nested networks whose functional boundaries do not necessarily correspond to the visually obvious boundaries of individual organisms.

This raises a fundamental systems question:

At what scale does information integration cease to be a property of an individual organism and become a property of an interacting biological community?

There is no reason to assume in advance that the answer corresponds to conventional taxonomic categories. Conversely, physical connectivity alone is insufficient to establish an integrated information-processing system. The appropriate boundary must be determined functionally: where does information generated in one region continue to predictably influence states and responses elsewhere?

The experimental methods proposed in Section 7 could, in principle, be extended progressively outward to investigate this boundary.

8.3 Ecological Timescales

Increasing spatial scale also requires reconsideration of temporal scale.

A fungal network spanning centimeters may exhibit relevant responses over minutes or hours. Interactions involving trees, fungal networks, soil microbial communities, and seasonal environmental cycles may unfold over days, months, or years. Ecological succession and long-term changes in network organization can extend over still greater intervals.

The Spatial–Temporal Scale Hypothesis therefore suggests that apparent slowness should not automatically be interpreted as absence of integration. The relevant question remains whether information persists and interacts on timescales appropriate to the processes occurring at that spatial scale.

This does not imply that larger systems necessarily possess slower cognition. Indeed, it does not establish cognition at all. It proposes only that an investigation of distributed biological organization must employ observational intervals appropriate to the system being studied.

An experiment lasting several hours may be sufficient to detect rapid fungal electrical responses while being fundamentally incapable of detecting a coordinated process whose relevant interval is seasonal.

8.4 From Ecosystem Integration to Planetary Organization

At the broadest scale, Earth's biosphere constitutes an interconnected system in which biological activity continuously modifies atmospheric composition, nutrient cycles, soils, hydrology, climate feedbacks, and the physical environment. These interactions produce forms of large-scale regulation and feedback without requiring any assumption of centralized control or conscious direction.

The existence of planetary feedback systems therefore provides no evidence by itself for planetary cognition.

Nevertheless, if information integration were eventually demonstrated across increasingly large biological networks, a new empirical question could be formulated:

Is there an upper spatial boundary beyond which biologically mediated information ceases to participate in coordinated system behavior?

This question is preferable to beginning with the proposition that a planet is conscious. It permits the scale of integration to be discovered rather than assumed.

The progression would therefore be empirical:

cell → hypha → mycelial network → interacting organisms → ecological community → ecosystem → biosphere.

At every level, the same requirements apply: information must be detectable, its propagation or influence measurable, its interaction with other information demonstrable, and its effects upon subsequent system behavior reproducible.

There may be sharp boundaries along this progression. Integration may prove highly developed within individual mycelia but weak between separate organisms. It may operate across symbiotic partnerships but disappear at ecosystem scale. Alternatively, previously unrecognized forms of distributed coordination may emerge as larger networks are examined.

The hypothesis does not predict which outcome will occur.

8.5 Planetary Cognition as a Boundary Question

Only at this point does the phrase planetary-scale cognition become useful, and even then it should initially function as a boundary concept rather than a conclusion.

A hypothetical planetary cognitive system would not necessarily resemble a greatly enlarged animal brain. It might possess no central processor, no rapid global communication system, and no clearly identifiable anatomical boundary. If such a system were possible, its organization might instead be distributed among interacting biological networks operating through multiple signaling mechanisms and across multiple temporal scales.

Its characteristic processing interval might consequently bear little resemblance to human perception.

From the perspective of an organism whose meaningful behavioral interval is measured in seconds, a system whose significant state changes occur over years or centuries could appear effectively static. Conversely, processes humans classify as ecological succession, long-term adaptation, or biospheric feedback might—under a sufficiently broad hypothetical framework—constitute components of information processing at another scale.

At present, there is no empirical basis for making that stronger interpretation.

The scientific value of considering it lies elsewhere: it reminds us that our observational timescale can determine which forms of organization we are capable of detecting.

8.6 Distributed Rather Than Centralized Organization

If large-scale biological integration exists, there is no requirement that it converge upon a hidden planetary equivalent of a brain.

As discussed for individual mycelial networks, integration could be partially centralized, hierarchical, or highly distributed. At ecosystem scale, functional organization might emerge from relationships among many networks rather than from a single controlling structure.

The analogy with distributed memory is potentially useful here. Information can be represented through relationships among many components rather than residing at one exclusive location. A sufficiently distributed biological system might therefore retain consequences of previous states through changes in network structure, species relationships, chemical environments, resource distributions, or recurring dynamical patterns.

More speculative comparisons with holographic representation may serve as heuristic models for thinking about such distributed information, but no literal holographic mechanism is implied. Demonstrating distributed representation experimentally must precede attempts to explain its physical basis.

8.7 Pattern, Rhythm, and Large-Scale Communication

The possibility of distributed organization also raises questions about the form in which information might be represented.

Human communication encourages us to search for discrete symbols. Biological networks may instead employ continuously varying relationships among electrical, chemical, metabolic, spatial, and temporal processes. At sufficiently large scales, recurring cycles, oscillations, synchronization, and phase relationships could become more informative than individual events.

Such patterns might eventually be rendered through sonification or other transformations to make complex temporal relationships perceptible to human investigators. Sonification in this context would initially be an analytical technique rather than evidence that biological systems literally communicate through music.

A more consequential finding would occur if naturally occurring temporal patterns, when experimentally reproduced, elicited responses distinguishable from randomized patterns with equivalent physical characteristics. Such a result would suggest that temporal organization itself carries biological information.

Only after such evidence existed would analogies to musical structure or patterned biological language become scientifically productive.

8.8 A Necessary Boundary Between Hypothesis and Imagination

The larger possibilities considered in this section are deliberately speculative.

No evidence presently demonstrates that fungal networks constitute a planetary communication system, that ecosystems possess subjective experience, or that Earth functions as a conscious organism. These propositions should therefore not be presented as conclusions derived from fungal electrophysiology.

Their value is heuristic.

Scientific imagination is useful when it generates questions that can subsequently be constrained by observation. The danger arises when an attractive explanatory metaphor is mistaken for evidence.

We therefore propose maintaining a clear hierarchy:

Observation → measurable information → propagation → integration → retention → coordinated response → increasing spatial scale → speculative cognition.

Each step must earn the next.

Planetary-scale cognition should consequently be treated not as the premise of this investigation, but as its most distant boundary question.

If experiments ultimately reveal only local fungal signaling, the larger hypothesis should contract accordingly.

If they demonstrate robust integration across individual mycelial networks, the appropriate scale of investigation can expand.

If integration is subsequently demonstrated across interacting organisms or ecological systems, larger questions may legitimately follow.

The scientific task is therefore not to prove that a planetary intelligence exists.

It is to determine, experimentally, how far biological information integration extends.

Where that investigation ultimately leads should be decided by the evidence.

9. Discussion

The hypothesis developed in this paper begins with a comparatively limited proposition: mycelial networks should be investigated as distributed biological information-processing systems without assuming that neuronal organization provides the only meaningful model of biological cognition. This proposition does not require fungi to possess consciousness, subjective experience, language, intention, or any human-like form of thought. It requires only that their capacities for sensing, signal propagation, information integration, retention, and coordinated response be investigated experimentally at the spatial and temporal scales appropriate to fungal biology.

This distinction is essential because complex adaptive behavior can arise without cognition in any conventional sense. Biochemical feedback, growth regulation, resource gradients, ion transport, hydraulic processes, and local stimulus-response mechanisms may collectively produce behavior that appears purposeful to a human observer. A branching network capable of efficient resource allocation need not therefore be making decisions, just as an electrical fluctuation need not constitute a message.

The central problem is to determine whether these mechanisms remain primarily local or whether their interactions produce reproducible network-level states containing information unavailable from the individual components considered separately.

9.1 Avoiding Anthropomorphism

Perhaps the greatest conceptual risk in studying unconventional cognition is anthropomorphism. Terms such as “memory,” “decision,” “communication,” “learning,” and “language” carry meanings derived largely from animal and human experience. Applying them prematurely to fungi can imply capacities not demonstrated by the underlying observations.

The opposite error is also possible.

If cognitive terminology is reserved only for organisms possessing nervous systems similar to our own, biologically different forms of information processing may become invisible by definition. The methodological challenge is therefore to avoid both anthropomorphism and neurocentrism.

For this reason, the present hypothesis emphasizes operational descriptions. Rather than initially asking whether a fungus remembers, investigators can determine whether previous exposure produces a persistent change that predicts a later response. Rather than asking whether the network communicates, investigators can determine whether a state originating in one region reproducibly alters activity elsewhere through biological connectivity. Rather than asking whether the organism decides, investigators can measure whether competing inputs are integrated into alternative responses.

Terminology can follow evidence.

9.2 Alternative Explanations

Any apparent evidence for network-level information processing must be evaluated against simpler physiological explanations.

Electrical changes may result from ion transport associated with growth or metabolism. Apparent long-distance coordination may arise from common environmental influences such as temperature, humidity, substrate hydration, or mechanical disturbance. Repeated responses may reflect metabolic adaptation rather than memory. Changes in network architecture may result from local nutrient gradients rather than globally integrated information.

These alternatives are not inconveniences to be eliminated rhetorically. They are competing hypotheses that must be experimentally distinguished.

Indeed, identifying a conventional physiological explanation for an apparently complex behavior would itself advance understanding of fungal biology. The objective should therefore not be to defend fungal cognition but to determine which explanatory level best accounts for the observations.

9.3 The Problem of Measurement

A second limitation is methodological.

Fungal electrophysiology remains technically difficult. Extracellular recordings may be affected by electrode placement, substrate properties, hydration, environmental electrical noise, movement, and changes associated with growth. Different laboratories may employ different species, substrates, electrode configurations, filtering procedures, and definitions of electrical events.

These differences make comparison difficult and increase the possibility that apparently meaningful patterns reflect methodology rather than biology.

Standardization will therefore be important. Experimental protocols should document electrode characteristics, geometry, sampling rates, environmental conditions, substrate composition, fungal developmental state, and signal-processing procedures. Raw data should be preserved whenever possible so that alternative analytical methods can be applied independently.

Multimodal measurement may prove especially valuable. An electrical event accompanied by a reproducible calcium, chemical, metabolic, transport, or growth response provides stronger biological evidence than an electrical event considered in isolation.

9.4 Pattern Recognition and the Risk of Finding What We Seek

The complexity of fungal recordings creates another danger: complex datasets almost always contain patterns.

Modern computational methods can classify extremely subtle differences among experimental conditions. Machine learning may therefore become an important analytical tool, but high classification accuracy alone does not demonstrate biological meaning.

Models must generalize to previously unseen data. Experimental conditions should be blinded. Appropriate randomized controls must be included. Ideally, models trained on one independently grown network should be tested on another.

The strongest evidence will occur when a detected pattern does more than identify the stimulus that preceded it: it should also predict a subsequent biological response.

Prediction provides a powerful safeguard against retrospective interpretation.

9.5 Individual Variation

Mycelial networks are living systems with histories.

Two genetically similar fungal cultures may develop different architectures because they encounter different microscopic conditions during growth. Natural networks will exhibit still greater variation arising from age, resource distribution, microbial interactions, physical disturbance, and environmental history.

Such variation may initially complicate the search for generalizable signal patterns.

It may also prove informative.

If information is partly represented in network architecture or persistent physiological state, individual history should influence how subsequent information is processed. Variation would then be not merely experimental noise but a potential characteristic of the system under investigation.

The challenge will be to distinguish biologically meaningful individuality from uncontrolled experimental variability.

9.6 Scale Does Not Guarantee Cognition

A particularly important limitation concerns the relationship between network size and information-processing capacity.

The Spatial–Temporal Scale Hypothesis does not imply that a larger fungal network is necessarily more intelligent, more integrated, or more conscious than a smaller one. Increasing size creates communication delays, metabolic costs, noise, vulnerability to fragmentation, and greater demands upon coordination.

Large networks may compensate through redundancy, modularity, hierarchical organization, persistent states, or changing topology. Alternatively, functional integration may remain confined to relatively small regions even within physically extensive mycelia.

Determining this boundary is one of the most important experimental objectives proposed here.

A physically continuous fungal network should therefore not automatically be regarded as a single informational unit. Functional integration must be demonstrated.

9.7 Cognition and Consciousness Must Remain Separate Questions

Even convincing evidence for distributed information processing would not demonstrate consciousness.

A system might discriminate among environmental conditions, integrate multiple signals, retain previous states, and modify subsequent responses while providing no evidence concerning subjective experience.

Consciousness presents additional conceptual and experimental problems that extend far beyond the scope of the present hypothesis.

We therefore recommend maintaining a deliberate separation:

information processing is experimentally approachable; cognition requires careful operational definition; consciousness remains a substantially stronger claim.

This hierarchy prevents evidence at one level from being automatically promoted to another.

9.8 What Would Constitute Progress?

The value of the proposed research program does not depend upon demonstrating fungal intelligence.

Several possible outcomes would represent scientific progress.

If fungal electrical events prove largely metabolic and local, improved electrophysiological methods will still have clarified fungal physiology.

If long-distance signaling is demonstrated but information integration is not, fungi will nevertheless provide valuable models of distributed biological communication.

If history-dependent network states are demonstrated, they may reveal mechanisms of biological adaptation and persistence distinct from nervous-system memory.

If multiple spatially separated signals are shown to interact reproducibly and predict subsequent network behavior, stronger claims concerning distributed information processing would become justified.

Only evidence accumulated across these stages should motivate increasingly cognitive interpretations.

9.9 Broader Significance

Understanding fungal information processing may have consequences beyond the question of cognition.

Fungal networks influence decomposition, nutrient cycling, plant interactions, soil structure, and ecosystem function. Better understanding of how these networks coordinate activity could therefore contribute to ecology, agriculture, forestry, fungal biotechnology, biomaterials, unconventional computing, and environmental monitoring.

Fungal systems may also provide useful comparative models for studying how biological networks solve problems without centralized control. Such principles could inform artificial distributed systems and adaptive network design independently of whether fungi ultimately warrant cognitive terminology.

The investigation is therefore scientifically worthwhile even if its most speculative extensions prove incorrect.

9.10 The Proper Position of the Hypothesis

The strongest form of the present proposal is not that fungi are intelligent.

It is that we do not yet know the upper limits of information integration within large living mycelial networks, and those limits can be investigated experimentally.

This formulation deliberately leaves several possible outcomes open.

The network may prove to be a sophisticated but fundamentally local physiological system.

It may exhibit long-distance communication without substantial integration.

It may demonstrate distributed memory-like and decision-like properties sufficient to justify carefully defined forms of basal cognition.

Or it may reveal organizational principles for which existing terminology is inadequate.

The appropriate interpretation should emerge from experiment rather than expectation.

The more speculative possibility of ecosystem or planetary-scale cognition should therefore remain outside the evidentiary core of the hypothesis unless and until integration is demonstrated across progressively larger biological scales. Such possibilities can guide the formulation of questions, but they should not determine the answers.

The purpose of this paper is consequently not to enlarge the definition of intelligence until fungi fit within it.

It is to enlarge the investigation sufficiently that we can discover what fungi actually do.

10. Conclusion

Fungal mycelium represents a biological architecture fundamentally different from the centralized nervous systems through which cognition is most familiar to us. Its branching and interconnected structure permits environmental sensing, resource redistribution, physiological signaling, adaptive growth, and continual reorganization across space and time. These properties do not demonstrate cognition, but they provide sufficient grounds to investigate mycelium as a distributed biological information-processing system.

We have proposed that the informational capacity of such a system cannot be evaluated by signaling speed alone. Network dimensions, topology, signal persistence, physiological state, and the characteristic timescale of relevant environmental processes must be considered together. A slowly propagating signal may remain functionally significant if it persists long enough to interact with other information and influence subsequent network behavior. The apparent slowness of fungal activity relative to neuronal transmission therefore represents an experimental variable rather than a reason for excluding complex information processing in advance.

The central hypothesis can be tested without attributing consciousness, intention, or language to fungi. Controlled experiments can determine whether distinct environmental events generate distinguishable network states; whether those states propagate through biological connectivity; whether information from spatially separated locations interacts; whether previous events alter later responses; and whether integration depends upon localized hubs or emerges from distributed network dynamics. Such experiments can establish not only whether integration occurs, but also its spatial and temporal limits.

The larger implications should follow the evidence. Demonstration of information integration within individual mycelial networks would justify investigation at greater spatial scales and across interacting organisms. Failure to demonstrate such integration would constrain the hypothesis and clarify the limits of fungal coordination. Either outcome would improve understanding of how complex living networks organize and respond to information.

The immediate question is therefore neither whether fungi think as humans do nor whether a planetary intelligence exists. It is simpler and experimentally approachable:

How much information can a living network without a brain acquire, integrate, retain, and use?

Answering that question may reveal that the boundaries of biological information processing are narrower than proposed here—or considerably broader than we presently recognize.

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The author declares no conflicts of interest.

Author Contributions

Donald B. Barrett: conceptualization, hypothesis development, project coordination, critical review, and approval of the final manuscript.

Declaration of Generative AI and AI-Assisted Technologies

Generative artificial intelligence was used as an editorial and organizational aid during manuscript preparation. The author developed the central hypothesis, directed the manuscript's conceptual structure, evaluated its scientific content, reviewed the references, and accepts full responsibility for the final text.

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