# Frame by frame? A contrasting research framework for time experience

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## Abstract

The way we experience the world has an inherently temporal aspect; events follow the ones before in a linear fashion. Our experience presents to us in the form of a fleeting present with no clearly demarcated beginning or end, always imbued within an evanescent stream of perceptions and thoughts. While different approaches from cognitive science and related fields share the view that this temporal aspect is fundamental to our phenomenology, our experience of time seems in direct tension with the physically grounded, widespread notion of discrete state-space transitions that underpin so much of modern cognitive science and artificial life. In other words, while state-space transitions seem to correctly characterize most cognitive phenomena, it isn't clear how this relates to the fluid and evanescent temporality of our experience. We present a formal framework centered on the idea of how sensory-perception incompleteness translates into temporally dense constructions of the perceptual present.

## Introduction

It seems *prima facie* problematic to ground the temporal aspect of experience in the state-space dynamics common in modern cognitive science and artificial life. On the one hand, it seems like the fundamental temporal aspect of our experience emerges from the perception of constant change; without the possibility of sensing changes to the internal and external milieu, there would not only cease to be any perception of time, but also any perceptions at all (Kent and Wittman, 2021). On the other hand, any physical system is bound to the physical present insofar as the past and future states of that system don't actually exist. To state the problem: in order to sense change, the system would need to simultaneously consider more than one state; a form of extended present in which a collection of states could be observed to change. However, during such observations the (observer) system is itself undergoing change, which precludes any final confirmation of the initial observation.

It's because of this problem that the standard view seems to be that the grounding of phenomenological time is to be found in the discrete states of the (nervous) system. Indeed, we tend to think that, much like a film, it's by "connecting" the "frames" of discrete state-space dynamics that our phenomenology of time arises. However, it seems to us that this cannot really be the case, because the 'frames' of the film are the states of the system itself, so it isn't clear how those frames/states are connected without entering an infinite regress (each connection between states requires a new state). It is in this sense that we come face to face with a potential paradox. There is a mismatch between our phenomenology of time and how we experience the present moment as something fluid and open-ended, and how we model perception based on discrete state-space dynamics. Put another way, if temporality is underpinned by discrete states, why does our phenomenology not reflect this, by allowing us access to a clear cut concatenation of frames in which each present moment has a beginning and an end?

By discrete we refer to the fact that, even if we were to conceive everything as continuous, all standard models either use discrete states per se (e.g. Markov models), or ordered finite discrete states as an approximation to continuous states, or represent the system in terms of a sequence of states in a single point in time, each of those states being discrete (and infinitesimally short!). While this, in our opinion, may not pose a problem for sensory-action models, it becomes problematic when directly transferred to perceptual experience. To further illustrate this point; biologically speaking, underlying sensory machinery in most organisms is not instantaneous, requiring finite periods to operate, hence involving discrete (often asynchronous) sensory samplings (Liu et al., 2017), and even for continuous sensing (i.e. always acting, responsive only to change) (Frye, 2015), there are associated intrinsic rates or time scales (e.g. delays, processing time, a period to 'refresh' the sensor, etc.), therefore, making the use of discrete states a correct idealization. Our assumption, nonetheless, is that the nature of sensory instances, as frequent or fast as they may be, will always respond to particular structural changes resulting in (even if minimal) time gaps. Such gaps, so we propose, can't be *filled* by taking infinitely shorter periods, but require some form of cognitive *temporal integration*, in order to account for fluidity of perception.

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One explanation might be that we sense the changing physical states of the internal and external milieu and synthesize that change as a kind of continual motion. Put another way, the fluid temporal aspect of phenomenology might arise from discrete sensory samplings which are presented to us as a continuous event. This is the position defended in this paper. We argue for a temporally dense (i.e. non instantaneous) minimal unit of experience, and illustrate how current approaches seem to be limited in their ability to provide this. In the final part of this paper, we present an alternative formal framework that provides a more satisfying solution to the problem described. One of the main contentions of this paper is that this issue, often disregarded derisively as a "philosophical problem", is actually a very real problem in how we understand the phenomenology of time and its relationship to physical time and to state-space dynamics. Ultimately, the solution lies in seeing how our phenomenology of time is much more than a mirror of the physics of time, and more an embodied construct similar in nature to our experience of color. We hope that what we present here may describe a basic, although relevant aspect of the necessary cognitive processes for eventually bridging life and mind in a naturalized manner.

## Phenomenology and temporality

In locating the minimal unit of phenomenological time, one thing is clear: it cannot be a static, discrete frame. Rather, we propose that a more intuitive and plausible way to think of this minimal unit is as a lapse, which is to say, short duration of time of varying length. These moment-to-moment lapses may vary in length, but form the foundational unit of how we experience time. Even when we engage our mental time-travel abilities, casting ourselves forward to hypothetical events or remembering vividly some past experience, we never actually leave these present-moment lapses. What's more, these lapses themselves have no clear cut off at their beginning or end, instead they form an overlapping stream. In short, the minimal unit of experiential time is not a discrete frame, but something more vaguely defined, more fluid. This is the account of experiential time we advance, but it is inline with accounts given by both William James and especially Maurice Merleau-Ponty.

James (1890) referred to this foundational unit as 'the specious present', which he described as "the short duration of which we are immediately and incessantly sensible." The specious present is, essentially, defined as a short period of time over which we observe persistence and change. For James, our experience of the present is in some sense extended (i.e. specious) and its boundaries are vague; it cannot be said to have any boundaries as such. While James' observations could seem trivial, the hypothetical incompatibility between physical states and perception of change has been a matter of long discussion (Miller, 1984; Dainton, 2014).

In this context, Merleau-Ponty (2012, ch.3) develops these ideas further, fundamentally casting doubt on our regular intuition of a perceptual stream as the result of discrete juxtaposed instances, by denying the possible appearance of (a lapse of) time from physical or conscious states. Roughly, the argument can be presented as follows; if we agree that any physical entity exists in a given physical present space and time, any state of the system which isn't that specific state that does not actually coexist with it (e.g. its past or future states). As described, a lapse of time is not simply the present state of the system, and so a lapse of time couldn't arise from pure physical unfolding, because their present is always their current state and, therefore, the existence of (an intrinsic) temporal dimension would be precluded by the absence of an observer for whom things would change. As Penrose (1994) put it, space-time does not require a passage of time at all, only consciousness does.

In the same vein, we couldn't expect intrinsic time to be the result of a succession of (instantaneous) conscious states, because, likewise physical states, conscious states are entities that are supposed to exist in the present (i.e. our past/future experiences do not exist in the present, even if we can experience memories from the past, or imagine hypothetical scenarios such as the future, these are always experienced in the present). Indeed, it would be impossible for time/change to be experienced, insofar as a temporal dimension requires some minimal extension that could not be produced, or derived, from punctual consecutive states, independently of their nature.

The conclusion to which Merleau-Ponty arrives is that the nature of experience must itself be temporal and that our cognitive temporal distinctions of succession and order are to be found as distinctions within it, by the eventual appearance of a phenomenological perspective from where such distinctions become pertinent. In this sense, a minimal form of experience could be conceived as more akin to a perceptual whole, along the lines of a primitive *pure experience* as posed by Taguchi (2018), where ulterior, more complex cognitive distinctions such as 'before' or 'after' could be grounded.

## Frame by frame?

Modern frameworks in cognitive science and artificial life rely on discrete state-space dynamics. They describe how physical (living) systems transition from one state to another, and these transitions are represented as instantaneous, lest we be condemned to Zeno's paradox. In this section, we briefly review how these frameworks conceive of state space transitions in order to see how none of them has yet offered a plausible approach for translating these dynamics into an experiential unit of phenomenological time.

The problem seem to stem from conflating physical time with our experience of time, whereby the search for the grounding for a temporal dimension has been the physical, instead of a more suitable mental realm (Dorato and

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Wittman, 2015). This mismatching association was also noted by Varela (1999) in terms of a reducible, computational time (illustrated by the sequential operation of a Turing machine) versus the *textured* and irreducible temporality that seems to underpin our conscious experience.

In this respect, an illustrative fact is that, in spite of the phenomenological relevance of time experience, several neuroscientific approaches to consciousness (like Global Neuronal Workspace Theory or Integrated Information Theory) are heavily focused on too narrow lapses or discrete time notions (Kent and Wittman, 2021).

Traditional Enactivism has made much progress in recent years through an adoption of dynamical systems theory, solving some thorny theoretical issues in core ideas about autopoiesis and autonomy, and providing a formal construct to link the embodied, enactive understanding of autonomy with further concepts such as operational closure (Barandiaran, 2017), adaptivity (Di Paolo, 2005), precariousness (Beer and Di Paolo, 2023) or sensorimotor habits (Egbert and Barandiaran, 2014). Within this framework, one core notion that necessarily involves a temporal aspect is normativity (Di Paolo et al., 2017, p.120). This, minimally, describes the property that living systems have of being intrinsically attuned to whether or not events are conducive or not to their ongoing viability (Varela, 1997; Froese, 2021).

One question that arises here is the following: how does an embodied system that is in continuous change, and doesn't make use of any form of representation, recognise these tendencies (the utility of a particular attractor state). How is change perceived without representational access to some form of information stemming from two or more of its (present and past) states, such that it can perform some form of evaluation? This is represented in Figure 1; where, by comparing the transitions $S_1 -> S_2$ and $S_x -> S_2$, we can see that the former is pushing the system from a 'good' state towards the limits of its viability domain, while the latter, which is also transitioning into $S_2$, is making it so from even more dire circumstances. How, and when, does this system make-sense of these changes as being good or bad? If the system does not posses any form of mindful representation that would enable it to perceive change, then we must assume that there are embodied equilibrating state dynamics that continuously regulate its behavior through system-environment state-based feedback loops. However, if its adaptive mechanisms can account for this, there would be no clear reason to invoke a meaningful normativity or sense-making.

This particular point has been criticized by radical enactivism (REC) (Hutto and Myin, 2017) stressing this representational contradiction, while positing ur-intentionality as an alternative. Nevertheless, even if ur-intentionality is sound about evolutionary cognitive amalgamation, its connection to perceptual experience is unclear (Abramova and Villalobos, 2015; Rowlands, 2015) and in this respect, REC

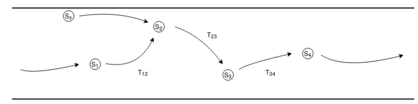


Figure 1: Two different states ($S_1$ and $S_x$), with opposite viability implications and leading to the same state ($S_2$). How do these transitions entail different meanings for the system at $S_2$, without an extended perception accounting for changes becoming good or bad?

relies on normativity as much as traditional enactivism. In brief, while the enactive notion of normativity may very well be correct, in our opinion, the lack of a naturalized temporal aspect is still limiting its formal characterization.

Predictive processing theories fare no better. One of the great attractions of these theories (which include Active Inference, the Bayesian Brain Hypothesis, and so on), is that unlike enactivism, they speak to the contents of our subjective experience (Seth and Tsakiris, 2018). PP theories introduce a specific, Bayes approximate cognitive architecture, wherein a system updates its beliefs about the environment and itself based on incoming sensory data (Clark, 2013). One feature of this Bayesian cognitive architecture is that those priors have a pronounced "top-down" effect on how we perceive the world. Indeed, subjective conscious experience has been studied in terms of "controlled hallucination" partly constituted by expectation (Suzuki et al., 2017). The promise here is that perhaps this role played by top-down expectation in shaping experience can play some key role in translating the physical states of the system into our subjective temporal experience (Friston, 2018).

However, this is a non-starter in terms of solving our problem. Under PP, systems are still modeled as moving along a trajectory in a discrete state space, no different to modeling under any other framework. As we mentioned, the problem isn't with modeling methods per se. Rather, the problem lies in moving from states of the system (as modeled) to "states" of experience. PP theories are forming the basis of exciting new work in computational neuro-phenomenology, but one major point of debate is how to legitimately move from computational, discrete time step models, to the messiness of human subjective experience. The problem presented in this paper is just one example of a context in which this problem arises.

The Integrated Information Theory of consciousness (IIT) has gained recognition by undertaking phenomenological research from the opposite direction, as well as by providing a formal set for measurements based on the assumed identity between consciousness and causal power (Tononi and Koch, 2015). As presented in its latest version (Oizumi et al., 2014), the integrated information (Phi) generated at any given time by the causal structure of a conscious system would be the measurable correlate of its conscious experi-

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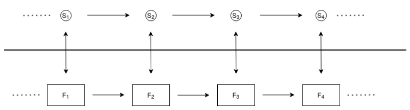

Figure 2: A minimal illustration of the state-experience correlation problem. Circles represent consecutive states. Rectangles, the assumed correlated frames of experience. A perceptual stream requires a form of continuity that does not seem possible from the pure juxtaposition of discrete instances of this kind

ence. The *locus* of experience, in turn, would be the most informative part of system (or the whole) with the highest Phi, while all the remaining subsets would be 'spontaneously' disregarded following a winner-takes-all (WTA) rule. The latter (referred as the exclusion postulate), is a quite controversial aspect of the IIT, especially in the current context. While its purpose is to delimit the (conscious) system spatially and temporally, as well as its correlated phenomenological contents, by appealing to parsimony; It doesn't offer a naturalized mechanism, nor a strong enough justification for it (Merker et al., 2021), even more when considering the strength of its claims.

Similarly to other approaches, the IIT takes the states of a given system in discrete time-frames and identifies such states with the content of consciousness. At this point, the question seems to pose itself: how could the information from a discrete frame represent change? The problem is, once again, the idea of an instantaneous/duration-less hypothetical grounding source (causal power in this case) for a temporal experience that is, by definition, extended in time. In fact, in our view, when the IIT asserts that there is a exclusive temporal grain through which temporal experience unfolds given its causal dynamics, it is conflating the physical grain in which the system is acting, with an experiential temporal grain which has a very different nature.

## What is physical and what is not

Now that we have a clearer understanding of our problem, we could summarize it as follows: given that experience must be somehow grounded on the physical states of a system, consecutive state transitions should give rise to different consecutive experiences. However, the discrete, non-temporal nature of these states (and their correlated experiences), doesn't seem to allow the conformation of a temporally extended unit of perception. This is what we have termed the illusion of a paradox and it is very simply schematized in fig. 2.

In simple words, the contradiction seems to arise from the impossibility of putting together a collection of states into a unit of experience that could account for perception of change within a seemingly unified stream. In our view, in order to deal with this issue, conceptual clarifications and formal re-examination are required. With these purposes in mind, let's begin by building up by recapitulating from the basics:

*i. Experience is inherently temporal*

As we have discussed throughout this work, any form of experience should account for a minimal intrinsic temporality, so that events can be perceived in terms of change; pain can only *become* painful within a lapse of experience, as if it were to be otherwise, it wouldn't be perceived as a change (even if possibly acted upon). In this sense, a temporal dimension may not be sufficient, but it seems at least necessary for phenomenological experience.

*ii. Cognitive systems exist in physical time*

Cognitive systems not only occupy a given point in space and time, but they are also confined into that point, which for them is their physical present. The notion of (instantaneous) states of a system, that correspond to punctual physical frames, even if an idealization, is conceptually correct in this regard, because it reflects the impossible coexistence of different (past, future) time instances with the present one.

*iii. Sensorimotor action is discrete*

Biological systems undergo changes that can be thought of as discrete in relation to a faster, uninterrupted physical time flow. While organic autonomous activity is intrinsically continuous (and we often model it this way), sensory samplings (insofar actions by structural change) occur at lower rates than many physical changes for which a one-to-one correspondence is impossible. In this respect, an important aspect underlying the particular selectivity of living systems is the nature of their temporal unraveling (we may compare the sensory-action pace of a tree with that of a fly, for instance).

*iv. Cognition does not necessarily entail experience*

In despite of intuitive considerations, there is no fundamental reason to believe that life or minimal cognition entail sentience per se (not yet at least). While we reckon that cognition does ground the processes required for experience and even if it is certainly arguable that life implies cognition, insofar cognition is understood as a form of organic (although syntactic) intelligence; if our premise about a need for a temporal aspect for phenomenological experience hold, cognitive systems without an intrinsic temporality may be conceived as phenomenologically void.

*v. Perception is subjective*

One of the most influential criticisms from enactivist approaches to classic computationalism was directed towards the naive idea of internal symbolic representations hypothetically mirroring objectively external reality. Moreover, early embodied accounts of cognition were able to show how the particular nature of autonomous cognitive systems, along

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with system-environment interactions, will result in different forms of intrinsic coherence and specific sets of cognitive distinctions (Varela et al., 1991). While the gap from purely syntactic forms of distinctions (the ones that can be modelled in simple simulations) to perceptual distinctions is still a matter of debate, there is a vast literature confirming that perception is highly dependent on the subject of experience. Apparently simple things such as colors are not objectively real, but rather categorizations that are the consequence of an evolutionary history and cultural moulding.

*vi. Experience of time is subjective*

Given that we are unable to see reality 'as it is' (e.g. the range of wavelengths that we are able to visually distinguish is fairly limited), it would be contradictory to think that for time the case would be any different. In fact, we have argued that minimal units of experience must be temporally extended, even if physical states and changes, including sensory sampling, can be thought of as discrete and therefore perceptually disconnected in principle. In this sense, the phenomenon that we usually associate with our experience of time is not objective time, but a cognitive construct, which is grounded to some extent in physical reality, but which does not mirror it, or represent it objectively.

*vii. Sensing is not enough for perception*

This may seem counter-intuitive at first, but is quite straightforward if we think of perception in terms of perception of change. Actually, this is perhaps one of the reasons for the paradoxical view of experience as-/from- states.

Whenever we associate directly sensing with perception, we are unavoidably faced with a frame-by-frame substrate for experience. However, if we acknowledge sensing as physical state correspondences and perception as a subjective higher-level cognitive construct, this is not the case. We believe that perceptual experience only appears from the integration of non-simultaneous collections of primary non-perceptual (i.e. semantic-less) sensing instances.

If we were to put this in terms of information, we could say that the information that can be measured from sensory changes is less than the information that could be measured from a minimal unit of perception. Not only because one punctual frame does not allow observation of change, but also because single sensory changes are local and decentralized, while perceptual experience requires a form of coherent and more (even if not totally) global unification.

*viii. Sensory integration is unavoidably temporal*

Given that sensory samplings are in themselves insufficient for experience and considering that these samplings are consecutive in time, any form of perceptual integration or composition should need to account for a non-zero time lapse, hence conferring some degree to temporal extension to the result of the process of perceptual 'amalgamation'. Actually, if we consider that a sequence of fast sensory physical transitions is in place, integration into a frame should be more prone to incoherence than a temporal one.

In other words, if we assume sensory samplings as discrete, changes in the environment in between them should be the norm, rather than the exception. And because these samplings are incomplete perceptual instances that require some form of integration, if they were to be condensed into one static frame, there would be inconsistencies and some sort of mechanism would be needed to 'decide which sensory-frame to choose' (as with the WTA mechanism in the IIT). Furthermore, in our view, it would be this incompleteness what would force the (temporal) 'canvas' to be filled with 'patches' corresponding to different physical times, whereby the relation among the elements would be both spatial and temporal. There would not be any complete frame for one physical time, nor any completion for one feature across sensory frames; the whole unit would a kind of sparse graph-like structure, far from the metaphor of a solid block.

*ix. The present moment is not the physical present*

This follows quite straightforwardly from the need for a certain lapse of time (even if very short) for sensory and high-level cognitive structures to change. There will always be some delay between the physical present and our experience of it, even if very short. Moreover, insofar we have claimed that perceptual experience is made up from a set of sensory samplings, we are implying that a primitive form of memory or retention must be at play. Along these lines, our experience of the present is the experience of an immediate past, which is also slightly out of phase with respect to the sensorimotor structures acting in the physical present.

*x. Experience is a process*

Experience is not a property of physical objects or their states, these are perceptually experienced within our experience of the present moment. Discrete sensory stimuli, whether these are related to environmental circumstances (such as our relative position to a looming object) or to intrinsic autonomous activity (such as memories) are not temporal in nature, however, we are incapable of registering them as such. Phenomenologically speaking, rather than the illusion of a movie coming from a sequence of frames, it would be the illusion of distinguishable frames coming from a temporal minimal unit. Similarly to how we naturally endow a temporal aspect to a comic strip made of static frames, we perceive discrete stimuli as events because our experience is inherently a temporal process.

*xi. Perceptual transitions are incomplete*

The experience of the present is not only temporal in itself, it is perceived as an evanescent continuum with no clear cuts delimiting where a moment starts or ends. In this sense, even if considering minimal temporal perceptual units, the

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classical notion of state transitions would result in a sequence of disconnected lapses. In our view, the experience of continuity arises from incomplete perceptual transitions which are the consequence of the incomplete nature of the primary sensory samplings.

Referring to a classical analogy and imagining ourselves placed in a flowing stream, if we were to consider an idealized instantaneous time (like a photograph) and the subsequent one; would the water surrounding me be a new mass of water? If we were to take two pictures before the water moves, there would be no change to perceive. If all the water surrounding me would have changed before the second photograph, there wouldn't be perceptual change either, just two different disconnected frame-presents. Being thus, we believe that the perceived continuity of the present moment is underpinned by a constant and incomplete loose incorporation of primary samplings that transiently maintain part of the integrated whole.

It is because the minimal units of experience require a temporal aspect that this is possible, because (following on with the analogy) this gives rise to a *space* or domain that can account for a transient preservation. Otherwise, we would be back to temporally discrete domains (e.g. an imaginary line in the stream) where perception of change is impossible.

*xii. Experience of time is representational*

Temporal experience flows at a speed that does not correspond to physical time, nor to any of the sensory modalities of the system. And in this regard, we are forced to acknowledge that experience, insofar as it is a temporal construct, may be understood as a primordial form of representation; a preliminary grounding for ulterior phenomenological distinctions that cannot be provided by the pure unfolding of system-environment coupled transitions or enactions. By representation we do not intend an objective mirroring, nor a symbolic construction, but a cognitive entity which is physically grounded, although not physically tangible.

## A minimal framework for the construction of a perceptual lapse

As we mentioned above, our main premise is that one fundamental aspect of the distinction between sensory(motor) behavior and perception is temporality, or, in other words, that single samplings can't provide enough information to build up experience and that it is this inherent sensory incompleteness what results in a necessary temporal experience of change. Given thus, let's now consider a sequence ($\sigma$) of samplings ($x$), so that:

$$\sigma = (x_1, x_2, ..., x_n) \tag{1}$$

Where every sampling $x$ represents a sensory enactment, or a structurally selective and environmentally mediated change, such that:

$$x = (st_a, env_a) \rightarrow st_b \tag{2}$$

A very simple, although important observation is that every sampling occurs after some other, hence an integration of this sequence as a single instantaneous frame is, at least in principle, less straightforward than a temporal one. Along these lines, we believe that there must be some form of lossy retentional integration that can be abstracted as:

$$B = \sum_{j=1}^{m} \sum_{i=1}^{n} x_{i,j} \tag{3}$$

Where the outer sum corresponds to different sensory modalities and the inner to the sequence of sensory instances. In simple words, $B$ represents the ideal set of (asynchronous) samplings coming from different modalities that are to be perceptually integrated.

Even if very fast, any temporal integration will necessary be out-of-phase with respect to the physical present, therefore involving a primitive form of memory. We assume, however, that there would be impossible to retain a perfect representation of $B$, first because some retentional degradation must be in place; meaning that, for instance, when the third sampling is occurring, the first sampling wouldn't be there anymore, but some embodied compressed retentional form derived from it. We will refer to this as retentional encodings:

$$g(x) = f_{enc}(x) \tag{4}$$

Given that the formation of a perceptual lapse would require the retentional encoding over the sequence of samplings ($\sigma$), we can denote the process over such sequence by:

$$G(\sigma) = (g(x_1), g(x_2), ..., g(x_n)) \tag{5}$$

One important question at this point would be; how many elements does the $G$ set contain? In our view, there wouldn't be something like a fixed objective duration or fixed number of samplings, but a range within a threshold, determined by cognitive capacities and the nature of the events. This, we believe, should be measurable in terms of information (even if, of course, there is no real substance-like information involved).

For these purposes, if we take the simplest case and consider only one sensory modality, by loosely building on top of the notion of intrinsic information, we can conceive the information of one sensory(motor) transition to be equivalent to their distance in state space, considering the possibilities enabled by the (sampling) system's autonomous organization:

$$I(x_{ab}) = I(st_a \rightarrow st_b) = D_{org}(st_a || st_b) \tag{6}$$

Where $st_a$ is the state preceding $st_b$, so that the minimal number of elements required for $\sigma$ would, in principle, be

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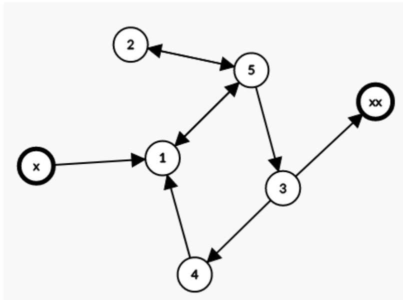


Figure 3: Minimal diagram of autonomous recursive operationality, where living states are denoted by numbers and invalid/dead states, by $x$ and $xx$. While both transitions $4 \rightarrow 1$ and $x \rightarrow 1$ are possible in mechanistic terms, we reckon that a system can't be conscious of what occurred to it before it was alive, so we take the latter transition to be irrelevant in this sense. Similarly, the transition $3 \rightarrow xx$, resulting in the destruction of the system, couldn't be perceived by it, even if causally possible.

two (i.e. one transition, even if we normally would expect a larger number to be the case). And where the subscript $org$ stands for the state space given by the autonomous organization of the system. The main difference between this and the IIT's notion of a causal structure is that, by considering its organization, some transitions that are possible (insofar physical mechanisms) are not really relevant given the structural state of the system and its related sensitivity. This is to say that, rather than the whole spectrum of possible mechanistic changes, we take as informative only the set of transitions which will result in the system being alive, as we reckon no cognitive distinction, even less conscious experiences, can be made otherwise (see figure 3 for a simple diagram). In this sense, while the organizational state space would also be built upon selectivity criteria, such selectivity would be derived from the autonomous dynamics of the system, instead of the other way around. We deem this necessary, because even if some conscious systems may have some understanding of the transitions that could lead to their destruction, this has implicit cognitive requirements (like memory, or reasoning) which in many occasions may not be in place for most living forms, including us.

As previously mentioned, the number of instances ($x$) within the sampling sequence ($\sigma$) would depend on the cognitive capacities of the system, which can be represented by an upper information threshold: $\gamma = max(I(H(\sigma)))$.

Insofar as $G(\sigma)$ is an instantiation of a form of immediate memory, the plausibility of an upper limit is based on similar thresholds of this type that are a documented fact for a range of related features (Cowan, 2001; Buschman et al., 2011), whereby, depending on how informative the incoming samplings are, the cognitive upper memory limit could be reached with few or several sensory samplings.

For a single modality, we could easily obtain the number of sensory instances being encoded by:

$$n_f = \frac{T_\sigma}{dt_m} \tag{7}$$

Where $T_\sigma$ represents the physical duration of the sampling sequence (that can be derived from $\gamma$) and $dt_m$ the sampling rate of the specific modality. This can also be applied to the multimodal case, assuming independent sampling rates for the different sensory systems involved. Following from this, we could represent a multimodal sequence of sensory changes as:

$$\sigma = \begin{bmatrix} x_1 & 0 & x_2 & 0 & x_3 & 0 & x_4 & \cdots & x_n \\ 0 & y_1 & 0 & 0 & y_2 & 0 & 0 & \cdots & y_n \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ z_1 & 0 & 0 & 0 & z_2 & 0 & 0 & \cdots & z_n \end{bmatrix} \tag{8}$$

Where $x$, $y$ and $z$ stand for different sensory modalities, and the zeroes, for simplicity's sake, for the inter-sampling periods. While retentional encodings for different sensory modalities would be cognitive processes occurring in different specialized areas, the encoding themselves all belong to the same working domain (e.g., spikes for neural systems). Being so, the notation for the overall process would be:

$$G(\sigma) = \begin{bmatrix} g_1(x_1) & 0 & g_1(x_2) & \cdots & g_1(x_n) \\ 0 & g_2(y_1) & 0 & \cdots & g_2(y_n) \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ g_3(z_1) & 0 & 0 & \cdots & g_3(z_n) \end{bmatrix} \tag{9}$$

Where the subindices for each encoding $g(x)$ indicate the a different modality and zeroes stand for an absence of sensory encodings at that time-frame. While the asynchronicity for $\sigma$ and $G(\sigma)$ are likely to be different, we have maintained the zeroes from the previous equation in order to stress that this property will propagate from the first to the second (even if not linearly) and that the sparsity of this matrix reflects the incompleteness of the sensory frames. While our idea is rather to set a conceptual framework, it may be in place to note that evidence of fitting cognitive processes has been described in insects (Stevens, 2015; Ardin et al., 2016).

Because $g(x)$ is an encoded form of $x$, i.e, a correlated structural transition in a different area triggered by the sensory sampling, we could measure the information related to it in the same fashion as $x$ and we could denote it as $I(g(x))$. We reckon, however, that a comparison between $I(x)$ and $I(g(x))$ wouldn't be pertinent, given the different nature of the cognitive structures in which they would take place. Notwithstanding, we may build on top of $I(g(x))$ to obtain an information measurement for $G(x)$, for which we believe, considering the sparsity of $G(\sigma)$, a compression

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measure would the better alternative:

$$Cr = \frac{I(G(\sigma))}{I(f_{comp}(G(\sigma)))} \tag{10}$$

Here, $Cr$ stands for the compression ratio, a complexity related measure that indicates the degree to which information can be compressed, preserving the original information, given its intrinsic entropy. The relevance of this measure, lies in our assumption that the larger factor for $Cr$ is the temporal component. In our view, the reason for this would be the highly asynchronous nature of the $g(x)$ instances from different channels, by which the rows in $G(\sigma)$ would be more regular and less predictable column-wise. It is important to note that we are not suggesting a temporal perceptual aspect to be present at this stage, but its feasibility is more likely with lower ratios.

Indeed, we hypothesize that the integration of the sensory encodings into a perceptual time lapse takes place following from it. This would be enabled by the projection (correlated patterns of structural change) of $G(\sigma)$ into a different region, where the non null $g(x)$ elements determine a further transitional composition. This process wouldn't always occur and, in fact, we believe that surpassing some lower informational threshold is an essential requirement for integration. Such a constraint seems pertinent to us in order to account for the discontinuity of experience (insofar as we have claimed that intrinsic temporality is not sufficient, although it is necessary for experience), hence, tracing a line between sensorimotor and regulatory cognitive processes that do not involve perception and can be described in terms of adaptive state-based properties, among others, which have grounded in them not a model (a mirror) of an external environment, but of other cognitive processes. A good example of this would be dreamless sleep, where multiple cognitive processes are taking place, even if we are not experiencing anything. We could define the most basic form of integration as a form of compressed column by column concatenation:

$$K(G(\sigma)) = f_k(G(\sigma)) \tag{11}$$

And obtain the information associated to it, from:

$$I(K(G(\sigma))) = \sum_{i=1}^{n} I(k_i) \tag{12}$$

Where $(k_1, k_2, ..., k_n)$ is the set of all the elements of $K(G(\sigma))$. Nonetheless, an actual integration process might be quite different from a concatenation of the samplings. We will denote this integration by:

$$H(G(\sigma)) = f_h(G(\sigma)) \tag{13}$$

Given that $K((G\sigma))$ is a non temporally integrated form of integration, the extent to which the information of $H(G(\sigma))$ is higher or lower than the information that could be measured from the summation of its frames would be an indicator of redundancy or synergy, so that:

$$\alpha = \frac{I(H(G(\sigma)))}{I(K(G(\sigma)))} \tag{14}$$

Where, assuming information values being higher than zero; $\alpha < 1$ would indicate predominant redundancy, while $\alpha > 1$, synergistic integration.

## Conclusions and further work

The main motivation for the current work was to propose an alternative starting point to what has been a longstanding problem in artificial life, artificial intelligence and cognitive science; namely, the quest for naturalizing and characterizing perceptual experience as something qualitatively different from the ephemeral material or cognitive processes that can be fully described by idealized discrete states. While we share the skepticism, as well as the growing impression that there are fundamental pieces still missing from our general framework, which otherwise seems to point into a paradoxical direction (Froese and Taguchi, 2019; Froese, 2022), we believe that there is still enough conceptual space to explore the relation between life, cognition and experience in a naturalized fashion; without the need to resort to arbitrary mind-substrate identifications, or to distantly related properties of (e.g. quantum) reality yet (even if this could turn out to be the case eventually).

Our work is still evidently mostly conceptual and very high-level and it requires further implementational and theoretical developments. Among them, we are particularly interested in the possible relation between intrinsic temporality and the notions of agency and anticipatory experience. Regarding the former, we believe that it would be interesting to study the possibility of intrinsic temporal mechanisms involved in the presentation of the present moment (insofar as an immediate past), as acting perceptually over the following present experience, and therefore, indirectly, over future sensorimotor routines. Similarly, we reckon that a possibly fruitful direction for research would be in terms of its compatibility with active inference and other related approaches, considering how, during an event, different modalities relate to the system's integrity more immediately than others and how anticipatory constructions become a part of the perceptual minimal unit, hence properly extended and matching the temporal aspect of our phenomenological experience.

We are also very interested in developing and using this framework to shed light on specific biological cases. For instance, and in order to make our hypothesis truly falsifiable, we are currently investigating possible second-order sensorimotor mechanisms that could account for integration of originally asynchronous local sensory instances in insects.

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