

The physiology of coordination: self-resolving diverse affinities via the sparse order in relevant noise

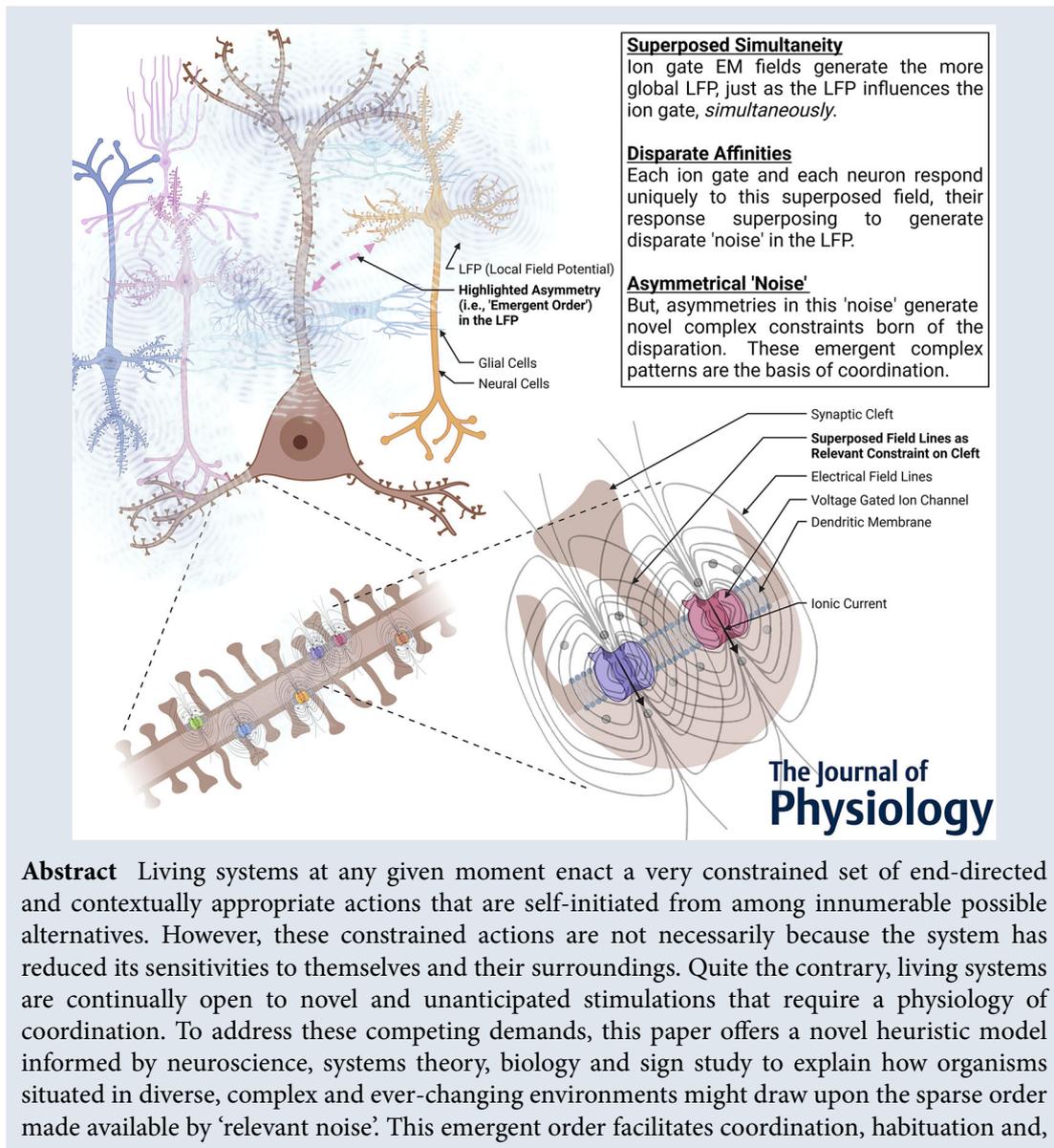
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Abstract Living systems at any given moment enact a very constrained set of end-directed and contextually appropriate actions that are self-initiated from among innumerable possible alternatives. However, these constrained actions are not necessarily because the system has reduced its sensitivities to themselves and their surroundings. Quite the contrary, living systems are continually open to novel and unanticipated stimulations that require a physiology of coordination. To address these competing demands, this paper offers a novel heuristic model informed by neuroscience, systems theory, biology and sign study to explain how organisms situated in diverse, complex and ever-changing environments might draw upon the sparse order made available by ‘relevant noise’. This emergent order facilitates coordination, habituation and,

ultimately, understanding of the world and its relevant affordances. Inspired by the burgeoning field of coordination dynamics and physiologist Denis Noble's concept of 'biological relativity', this model proposes a view of coordination on the neuronal level that is neither sequential nor stochastic, but instead implements a causal logic of phasic alignment, such that an organism's learned and inherited sets of diverse biological affinities and sympathies can be resolved into a continuous and complex range of patterns that will implement the kind of novel orientations and radical generativity required of such organisms to adaptively explore their environments and to learn from their experiences.

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Abstract figure legend Novel constraints emerging from the disparate 'noise'.

Introduction

The organization of all living systems is such that at any given moment, a very constrained set of actions are self-initiated from among innumerable possible alternatives. Both end-directed and contextually appropriate, this uncanny attribute of life must simultaneously consider both the current, yet ever-changing, state of the living agent, as well as that of its similarly dynamic and open environment. The everyday example of coordinating the act of grabbing a glass of water is explored in the section 'Semiotics in coordination'. In explaining this seemingly simple act, the notion of an 'internal model' has often been employed (Ashby, 1966; Rosen, 1985; Todorov, 2004). As one of our anonymous reviewers notes: 'for any living system to adaptively react to a tremendous number of external or internal environmental stimuli, it is necessary to build an internal model of the environment before the living system can use that model to assess how it should react; however, compared to how diverse environmental conditions can be, the mechanisms that a living system can use are fairly limited, which poses a contradiction.' This paper intends to explain how a living system self-resolves this 'contradiction', given an internal model that is reflective of a diverse and complex body, situated in a similarly diverse and complex milieu.

The authors are not physiologists. We have some expertise in neuroscience, environmental science, general biology and physical chemistry; we both share a more robust expertise in semiotics. As such, this paper is not well suited to review physiology for an audience of physiologists. Nevertheless, in the spirit of inter-disciplinary exchange, the broad questions above regarding living systems will be explored through the lens of a novel model (Bacigalupi, 2013, 2022) that is informed as much by neuroscience, thermodynamics and information theory as it is by general chemistry, biology and sign systems study. This 'two-cultures'-bridging inter-disciplinary model, intended as a heuristic lens, will focus on two highly complex physiological phenomena: the first, in 'Coordination in space', derives from the classic ethological work of Nikolai Bernstein in his book *The Co-ordination and Regulation of Movements* (1967), studying how repetitive movement in humans is never exactly the same; and the second, in the section 'Coordination in time (via phase)', is exemplified by the work of Saigusa et al. (2008) studying how amoebae memorize periodically occurring perturbations.

To contextualize the proposed heuristic model, the next section will discuss coordination in the context of the simple real-world example of rowers and the mathematics of phase, frequency and metastability within the discipline of coordination dynamics (Kelso, 2012; Tognoli et al.,

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2020). Based on this contextual background, we will then outline the novel concepts that remain to be elucidated in advancing our understanding of how coordination works in living systems. Addressing the observations of Bernstein and others, the section ‘Coordination in space’ will describe a hypothetical model that endeavours to fill the lacuna raised in the section ‘Coordination in context’. The section ‘Coordination in space’ will focus primarily on the capacity of living systems to coordinate themselves spatially at the intercellular level. In the section ‘Coordination in time (via phase)’, the proposed model will delve into the interior milieu of the cell, leveraging more well-known models of coordination (Strogatz, 2000; cf. Zhang et al., 2018), to hypothesize the capacity of cells to internalize patterns of external perturbation via the phasic coordination of diversely tuned chemical oscillators, which is just one example of the more general attribute of diversely tuned receptive affinities modelled by our hypothesis in the section ‘Coordination in space’. Our hypothesis will also endeavour to support Noble’s concept of *biological relativity* (2022a, 2012), that is, that living systems are neither exclusively bottom-up nor top-down in their functioning. Building on these sub-cellular dynamics, the penultimate section will move back up to the intercellular and organismic scale, to suggest how semiotically informed action–perception cycles, as has been hypothesized from von Uexküll (1926) to Fuster (2005), can sustain spatio-temporal coordination via the harnessing of sparse order in *relevant noise*, a concept to be discussed in detail throughout this paper.

Coordination in context

Before discussing the possibility of ‘relevant noise’ in an adaptive agent, we will first review how the phenomenon of coordination has been characterized by some contemporary cybernetic models. Starting with an everyday example, we can imagine a boat of eight rowers (for an example, search ‘rowing eight videos’ in your preferred browser). To be competitive, the rowers must be synchronized in all aspects of their stroke. This is particularly true for their frequency and phase: each rower needs to be at the same stroke rate and begin and end each stroke at the same time. Assuming the frequency is fixed, relative phase can be visualized mathematically by Fig. 1, where each rower is represented by a red circle on the large blue circle.

‘In the dynamics [of this mathematical model] ... every oscillator is effectively responding to the *collective* influence of all the other oscillators’ (Gherardini et al., 2018, p. 8, emphasis in original). In our rowing example, this means that each rower is not trying to synchronize with the boat by adjusting to each other rower sequentially. Instead, each rower is responding to a physical phenomenon that is analogous to the

coordination vector, which is represented by the vector r in Fig. 1. For each rower, this coordination vector is manifested as, for example, the sound of each oar hitting its respective oar lock. In a completely synchronized boat, this sound will be a single coherent sound. In contrast, the phasic relations illustrated in Fig. 1 are slightly out of phase, which would result in a ‘CLICK–click–click’ sound. Each rower can use this acoustic index as a kind of sonic terrain by which their subsequent behaviour is adjusted. For example, the straggling rowers can adjust their strokes to move towards the unified ‘CLICK’.

It is important to emphasize, however, that this mathematical model – although rigorous and illustrative – does not entail any means of explaining the majority of what actually happens in a boat of rowers trying to cohere upon each other’s behaviours. Even more complex models that build off the phasic circle above, such as the Kuramoto model (Kuramoto, 1984; Strogatz, 2000), likewise do not explain how the rowers are able to coordinate their behaviours. These models, in the authors’ view, are nevertheless useful in distinguishing steps along the way to complex coordination in actual living agents, as they characterize the relationship between coherence and decoherence and how constraints tighten and loosen to realize greater coordinative complexity (Bacigalupi, 2013).

Coordinative complexity, in this context, can increase in three distinct ways: (1) the number of phasic circles needed to characterize a system increases due to the co-existence of multiple distinct frequencies of the

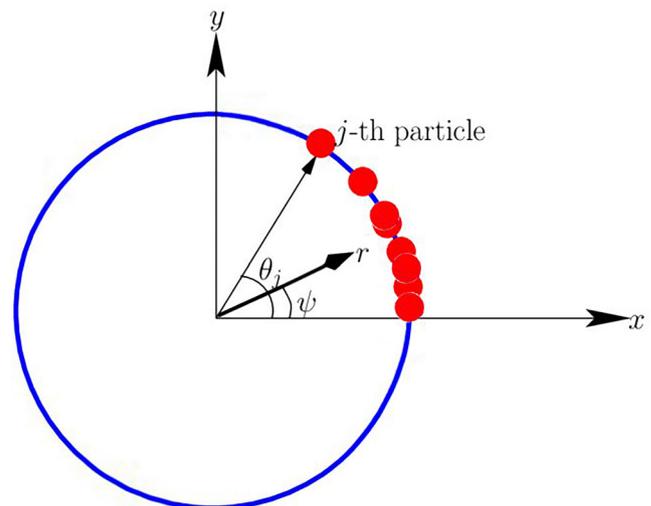


Figure 1. Phasic unit circle

Each red circle loosely represents the phasic relation of each rower to each other, when the frequency, or ‘stroke rate’, is held constant. The coordination vector, r , points to the centre of mass of red circles. The more coherent, or synchronized, the red circles, the longer vector r will be, up to unity. Conversely, r will equal zero when the red circles are distributed randomly around the unit circle. (Graphic adapted from Gherardini et al., 2018.)

dynamics, (2) the coherence of these distinct phasic circles (i.e. the coordination within each circle) increases, and (3) the correlations between the phasic circles increases. Intrinsic to this definition of complexity is the idea that once groups of oscillators tend to correlate, these distinct and persistent groups can then correlate with other persistent groups – and that this process can scale, through development, to groups of groups of groups, etc. From here forward, it is precisely this type of *coordinative complexity* that we will be referring to when we use the specialized use of the term ‘Complexity’ or ‘Complex’ with a capital C.

We believe that existing mathematical models may adeptly describe coordinative dynamics observable both in neurons and in groups of people. However, such models do not explain how novel and adaptive constraints emerge non-stochastically from the noise that is intrinsic to any system as it tends towards decoherence, which is precisely what we hope to do in this paper. Because, except for some empirical observations that noise seems to be useful in dynamical adaptive systems (Cannon & Kopell, 2015) and a recent discussion on turbulence (Hancock et al., 2023, p. 16), to the authors’ knowledge, current literature on bodily coordination does not incorporate the concept of *generative* noise into their models. Nevertheless, the discipline of coordination dynamics (Kelso, 1995, 2012; Tognoli et al., 2020) is particularly helpful in setting a rigorous foundation from which a more complete explanation of flexible, real-time and adaptive coordination in living systems will be proposed in the following sections.

Particularly useful in laying this foundation is a distinction between *multistability* and *metastability* (Hancock et al., 2023; Kelso, 2012). To better understand this distinction, let us return to our rowing example. The example above holds the frequency, that is the stroke rate, constant. But, of course, rowers must periodically change their stroke rate, and given two distinct stroke rates, we can posit two distinct phasic circles. In practice, rowers must learn to transition between these two rates, while trying to maintain phasic synchrony all the while. Prior to sufficient practice, a rowing crew will struggle through much trial and error, almost stochastically, trying to make this transition smoothly. This effortful and noisy transition is indicative of *multistability*: the transitioning between two discrete attractors in the possibility space, without an intermediary work pathway. In contrast, *metastability* is indicative of a crew that has become coordinated enough so that the former ‘effortful noise’ that was needed to be ejected from one local dynamical minimum in order to land in another will have become instead the source for relatively effortless adaptive work pathways between distinct stroke rates.

As counterintuitive as it might seem, such noise is a *necessary pre-condition for learning*, not only in the typical

understanding of stochastically trying something new, but also in the generative sense of *being* the source of novel and *relevant* constraints for incrementally more complex learning. As such, metastability is actually *less* stable than multistability (Hancock et al., 2023, p. 3), and this greater ‘looseness’ in learning becomes an adaptive flexibility (ibid). It is akin to learning how to hold a tool firmly but not too tightly in order to correctly accomplish a given task. On the contrary, the highly constrained dynamics modelled by multistability describes an attractor that is very stable. However, this singular and closed stability is at the cost of remaining sensitive to subtle asymmetries in the more global and, to be argued, relevant noise.

Such relevant noise and its contribution to understanding the metastable nature of coordination will be explained in the next section. To further shore up the foundation of this explanation, however, a few neurophysiological assumptions and their implications will be briefly outlined.

The first assumption is the well-established finding that the current in a neuron is modulated by numerous ion gates in that neuron. And, insofar as each gate both affects and is affected by both the intra- and inter-cellular potential, the cellular current at any instant is a result of this pervasive potential. Simultaneously, this potential is the superposed result of many distinct currents in multiple cells (Izhikevich, 2007, p. 6). In describing his early work on neuronal excitation behaviour, Denis Noble describes the dynamics of the Hodgkin cycle as follows (emphasis added):

Causation is formed at the same time by molecular dynamics (channel gating and ion movement) and the structural constraints from history (initial conditions) and boundaries (constraints by structure). There is no one-way around the cycle. *It all happens simultaneously. Contextual and dynamic causes are inextricably intertwined.* (Noble, 2022a, p. 5174)

On the same page, Noble contrasts the Hodgkin cycle with the Krebs cycle. The latter, for most analytical purposes, can be considered a stable and closed-loop molecular cycle, whereby causality is sequential from one chemical reaction to the next. The Hodgkin cycle, in contrast, cannot be conceived as merely *efficient causality* (in the sense of Aristotle’s four causes), but must also entail *formal causality*; there exist both the sequential chemistry of ionic gating currents (its *efficient cause*) and the potential heterogeneous gradient that suffuses the cellular milieu (its *formal cause*). Most importantly, notes Noble, these phenomena exist and affect each other *simultaneously*. Given this, Noble distinguishes the sequential and relatively closed-loop logic of the ‘cycle’ from that of the more simultaneous and distributed logic of the ‘ring’. Maintaining that all living adaptive systems are open in the thermodynamic sense, cybernetic models

tend to assert ‘closed’, by which we mean specifically sequential and stepwise, feedback loops, or ‘cycles’ in the non-‘ring’ sense of Noble, when explaining information, control, and coordination dynamics. However, in addition to the important distinction between such ‘cycles’ and ‘rings’ described by Noble, both Noble (2022a, pp. 5172–5174) and Izhikevich (2007, pp. 6–7) describe the limits of our mathematical models in the context of these significantly more complex – and likely mathematically intractable – ‘ring’ dynamics. In better characterizing coordination phenomena, this paper, too, argues that the latter kind of ‘ring’ dynamics are at work.

A second assumption, building on the first, is that the behaviour of each neuron is unique in its response to the same shared environment. In a section titled ‘Why are neurons different, and why do we care?’, Izhikevich (2007, p., 6) asks: ‘Why would two neurons respond completely differently to the same input?’ The answer is summarized by the statement that ‘The currents [manifesting at that moment] define what kind of dynamical system the neuron is’ (ibid). Said current is a function of the membrane potential, which is a function of, not only the potential at a given locus of measurement, but also the local field potential, which is a result of the many ionic and capacitive membrane currents within many surrounding cells (Izhikevich, 2007, p. 28). In the interstitial milieu between neurons, there is feedback, but it is not merely a sequential loop, given that each dynamical aspect of the neuronal milieu is both sender and receiver, simultaneously. And here we find ourselves back at our previous assumption: on this level, both local currents and more distributed potential exist and affect each other, *simultaneously at multiple scales*.

This second assumption has another important interpretation, especially when we consider that in such a scenario:

The resonant variable acts as a band-pass filter; it has no effect on oscillations with a period much smaller than its time constant; it damps oscillations having a period much larger than its time constant, because the variable oscillates in phase with the voltage fluctuations; it amplifies oscillations with a period that is about the same as its time constant. (Izhikevich 2007, pp. 130–131, emphasis added)

This ‘time constant’ is an intrinsic attribute of each neuron based on ‘the type of voltage- and Ca^{2+} -gated channels expressed by the neuron, the morphology of its dendritic tree, the location of the input, and other factors’ (ibid). It follows from this intrinsic attribute, and for the purposes of the model introduced in the next section, that in general, neurons – and even portions of neurons – have a particular affinity, or sympathy, in response to their shared milieu. This affinity is the unique way in which each neuron responds selectively, in the manner of a

band-pass filter, to select portions of the spectrum of frequencies exhibited by the surrounding field potential. Further empirical evidence for this assumption can be found in Leung and Yim (1991, pp. 262–272); Steriade (2000, p. 269); Buzsáki (2002); and Buzsáki et al. (2012).

The third and final assumption underlying the justification of our model further expands upon the first two assumptions into the wider neurophysiological milieu, by highlighting the fact that synaptic activity, in and of itself, is insufficient to account for collective neuronal activity. The local field potential, or just field potential, is composed of many sources both local and more distant (Herreras, 2016). Local currents and fields affect the global field just as the global affects the local, *simultaneously*. This is empirically established by the work of Christof Koch and others in the phenomenon of ephaptic coupling (Anastassiou & Koch, 2015; Anastassiou et al., 2010, 2011) and its relationship to the local field potential (Herreras, 2016; Herreras et al., 2023; Radman et al., 2007).

The above referenced empirical work on these phenomena so far appears to reinforce all the assumptions above regarding how local physical dynamics affect the global, while global dynamics simultaneously affect the local. However, what we suspect of all these studies, and what Herreras et al. (2023) state clearly, is the intent of finding all the individual causes for individual measurements of the collective field. As in principal component analysis and related techniques, one fruitful research goal is to be able to identify all the individual neuronal inputs to the field potential, near and far, in any arbitrary part of the nervous system. This will be important and illustrative research. Nevertheless, we suggest that this focus should not occlude another opportunity that, we will argue below, has substantial potential to improve our understanding of the underlying dynamic enabling complex and adaptive real-time coordination in living beings.

This dynamic can be analogically understood in part as the interference pattern between drops of rain on a pond, as illustrated in Fig. 2. Each drop sends distinct ripples into a common and continuous medium – in this case, water. These ripples superpose to create a higher-dimensional interference pattern. It is higher dimensional in the sense that the mathematical model for the ripples alone requires fewer dimensions than the model of their mutual interference. And, in the simple linear superposition of these waves, these novel dimensions are made available because of the physical nature of the common physical medium, which puts no constraints on the Complexity of the emergent superposed form. In fact, as is the case for the presence of ‘noise’ in any similarly continuous physical medium – from sound waves in the air to electromagnetic waves in free space – an arbitrary number of frequency components can be superposed in this medium, even *transfinite* numbers. And the resultant interference

pattern can entail asymmetries, which can themselves be harnessed, or embodied by a system developed to do so, to be constraints on subsequent dynamics. Herein lies the emergence of novel affinities that both come from, and are thus *about*, the system itself.

In the example of drops on a pond, for example, their interference pattern entails potential information about both their spatial and their temporal relationship to each other to an observer (or experiencer) of such patterns. Even for such experiencers, however, such perturbations are only *potential* information because linearly superposed waves will pass right through each other unaffected and dissipate, making them unavailable for map-building or information harvesting. To better understand the emergence of *actual* and relevant information, the next section builds off this observation in the context of the neuroscientific evidence summarized above to offer a novel model able to advance the conversation on how living systems embody ever more Complex capacities for adaptive coordination in real-time.

In introducing this novel model, the next section will also apply it as a heuristic lens through which the acquisition of arbitrarily 'Complex' spatial coordination can be better explained.

Coordination in space

The complex problem of spatial coordination will be characterized via the work of Nikolai Bernstein, and

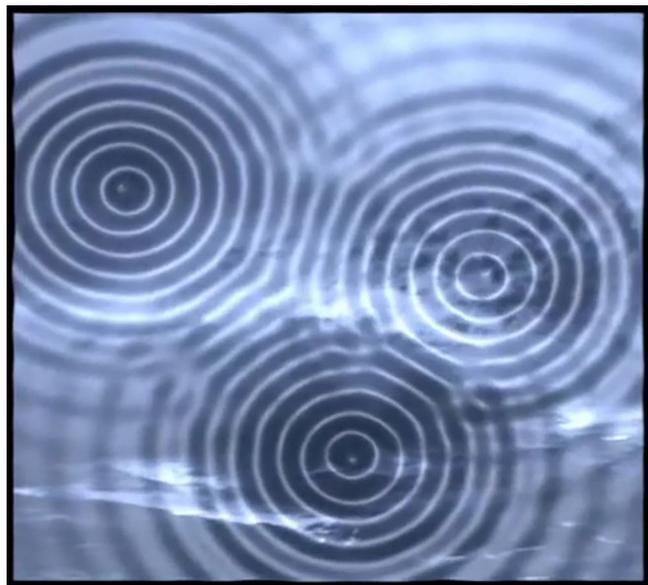


Figure 2. Drops on a pond

The continuous medium of water can entail an arbitrary number of distinct and independent patterns. The interference patterns illustrated here entail potential information about the spatial and temporal relations between each drop.

in particular his claim that '... straight lines ... are not proper to the motor field ..., nor are stable, identical lines. In biomechanics, this is manifested in that successive movements of cyclical nature never exactly repeat themselves' (1967, p. 48). More recently, Tuthill and Wilson (2016, p. 1022) observe the following:

The unpredictable structure of the natural world poses a problem for motor control systems. Because the environment and the body itself are always changing, a given motor command signal will not always result in an identical movement. A related problem is that internal frames of reference also shift during movement – for example, when limbs move relative to each other. In the terminology of control theory, flexible movements cannot be reliably executed in open-loop, but instead require closed-loop feedback from both external and internal sensors.

The first portion of this claim echoes the findings of Bernstein. However, as suggested in the section 'Coordination in context', the distinction between a 'cycle' and a 'ring' may be more productive than the one of an 'open loop' *versus* 'closed loop'. The empirical observations of both researchers quoted above admit the irreversibility of coordination: no stereotypic movement is ever *exactly* the same. Given these observations, a key question is this: *by what means do constantly novel behaviours arise*, if not via some causal relation between *both* local and global causality in the physiological feedback? Animals throughout the phylogenetic tree regularly exhibit not only 'flexible movements', but movements that are relevant to and adaptive within their respective real-time, ever-changing environments. It is this reality that motivates this paper's hypothesis that physiological processes are both dynamically complex and intrinsically generative, both in a local-sequential manner and a global-distributed manner, *simultaneously*.

To interrogate this hypothesis, our heuristic model will examine actual dynamical structures that, while observed in a given moment of the organism's development, possess inertial behaviours that are sometimes interpreted as 'circuits' or 'cycles'. Nevertheless, the idea that an organism's capacity to intrinsically develop a spatial map capable of real-time coordination is predicated on a closed feedback loop, circuit or conventionally understood 'cycle' will be problematized.

As a challenge and an alternative to this currently more prevalent approach to spatial coordination, a more open and generative model will be offered. Of course, there exists a temporal aspect to coordination at every scale in living systems, and we will return to this aspect in subsequent sections. However, for clarity in hypothesizing an already quite complex phenomenon, this section will focus on the ability of all motile animals to create a proprioceptive map of their own bodies over the course

of their initial development. How does the infant child, for example, or the nascent insect, learn where diverse aspects of their body are located in space? And once mapped, what must be the nature of this ‘map’ such that it may facilitate appropriate real-time movement? Because, if we warrant Bernstein’s claim that ‘successive movements of cyclical nature never exactly repeat themselves’, we must inquire as to whether this observation is a stochastic *bug* in the operation of the animal body or, as we shall argue, a *feature*.

In order to forward a rigorous hypothesis to these questions, a novel model is introduced that will entail three main attributes that are not common to legacy cybernetic and artificial neural network approaches (cf. Bacigalupi, 2023). These three attributes are summarized as follows: (1) a population of diversely sensitive nodes; (2) an interstitial, continuous, and pervasive medium that both moulds and is simultaneously moulded by the behaviour of these primary nodes; and (3) a more numerous population of secondary nodes able to discern emergent asymmetries, that is, order in the noise of an interstitial medium, as caused by the primary nodes. Based on this discernment, the secondary nodes facilitate the formation of ‘wired’ connections between

the primary nodes most likely responsible for those asymmetries.

Figure 3 illustrates the embodiment of these three attributes. The darker nodes in Fig. 3 are the primary nodes that have a unique resonant frequency, as noted; this is the first attribute above. For example, a C Major chord is composed of notes whose frequencies are similar to the resonant frequency of specific primary nodes. This heuristic model posits that sensitivity to distinct signals in their milieu can stimulate primary nodes, which, when a threshold is reached, emit their own pulse back out into the surrounding milieu, creating the constructive interference pattern as illustrated. This interference pattern is an emergent ‘figure’, which is in contrast to the surrounding ‘ground’. In actuality, this so-called ground is itself what we call *relevant noise*. It is noise because it is composed of an arbitrary number of superposed signals, *which are independent of each other*. It is *relevant noise* because it is mainly populated by signals which are the unique, yet physically independent, emissions of the primary nodes; this is the second attribute listed above. When select primary nodes are co-stimulated, it is their constructive interference and/or beat frequencies in the common medium that can be amplified above

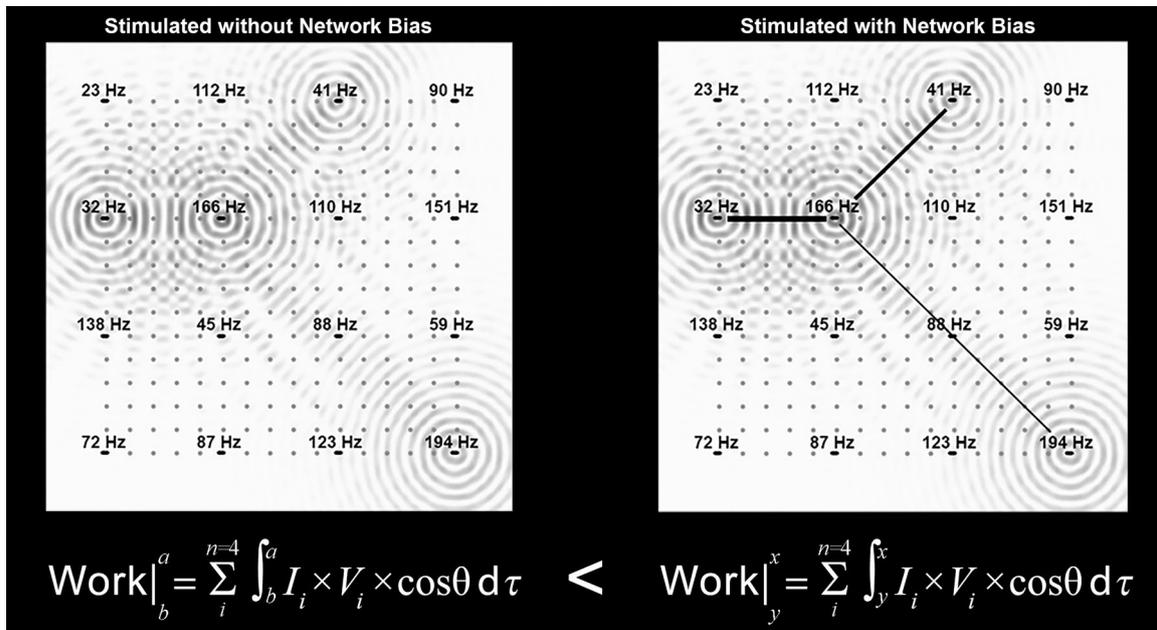


Figure 3. Adaptive work

Here, the work under investigation is understood in terms of current (I_i), voltage (V_i) (note that the scaler values of I_i and V_i in the work equations of the figure are the root mean square (rms) of alternating current and voltage in the measured circuit) and the phasic relation between them ($\cos\theta$), which in this context is called the *power factor*. In this form, these three terms are the *real power* of a given node. The work of each node is then the integral of this *real power*, given a particular interval. The claim illustrated here is that work between time interval (a, b) is less than the work measured between interval (x, y). This is because the accreted interconnections in the system during the second time interval (x, y) manifest circuits that have biased themselves such that phasic coherence, or alignment, has increased, which results in $\cos\theta$, the *power factor*, approaching (but never reaching) its maximum value of unity. This increases the actual or *real power* available to do work by the developing system. (Graphic adapted from Bacigalupi, 2013.)

the background noise. Subsequently, the more numerous secondary nodes will be able to discern this emergent sparse order. This is the basis upon which the system non-stochastically re-wires itself, thereby biasing itself to be more sensitive to more ‘Complex’ and previously sensed patterns when they recur, which is the third model attribute. (As introduced earlier, this term, ‘Complex’, when capitalized, has a rigorous definition in the context of this heuristic model as introduced in Bacigalupi (2013). Although independently derived, it can be likened to Tononi’s mathematical definition of Phi (2004). In contrast to Tononi’s proposal, however, our heuristic model argues that such ‘Complexity’, or Phi, is merely one attribute of cognition or consciousness, *but not its equivalent*). This embodiment is a model for how novel, higher-order, or more ‘Complex’, dimensions can radically emerge (Longo et al., 2012). These then become the basis for novel constraints and behaviours, as will be discussed below.

This novel model proposes that the interference pattern – the result of being stimulated by a particular pattern, for example, C Major – can function as an index of recurring consequences by which the system can create specific network connections. These *actual* connections, based on the *virtual* interference pattern, bias the network to increase the phasic alignment between *I* and *V*, when the ‘learned’ pattern reoccurs. It is because of this, we argue, that living systems are able to do more *adaptive work* than non-living systems, because they have become more sensitive to those particularly relevant patterns that tend to recur in their environments, and that have consequences for the functioning and/or well-being of the organism.

But how does this model help explain the capacity for animal organisms to map themselves through development? And, furthermore, how does this explain Bernstein’s observation that movements never repeat themselves?

For the first question, we can imagine pressure-sensitive nerves in the skin as illustrated in Fig. 4. Two different adjacent arrays, similar to those in Fig. 3, each with their own diverse tunings can represent arrays of nerves in the skin: that is, stimulation patch A and B. Like a tuning fork, each stimulated neuron, or node, in each patch will emit its own firing pattern into the extracellular milieu between neurons. Central to this model is that, in addition to action potentials being propagated up the radial and musculocutaneous nerves, there is also the electromagnetic field. Like a bell being rung or drops on a pond, both the observable action potentials and their associated field dynamics are transduced up the arm and to the somatosensory cortex. In Shannonian terms, the *communication channel* is *both* the distinct neural firing of each neuron *and* the EM field that both moulds and is moulded by that firing, *simultaneously* (Hales, 2014; Herreras et al., 2023).

A similar, yet distinct, example of this sensory binding within a single modality is the phenomenon of magenta via trichromatic vision in humans, as illustrated in Fig. 5. Analogous to the distinct stimulation patches, each composed of an array of diversely sensitive cells, trichromatic vision entails three distinct populations of retinal cells, each also composed of diversely sensitive cells. However, despite – or more likely because of – these diverse structures within structures, co-stimulation

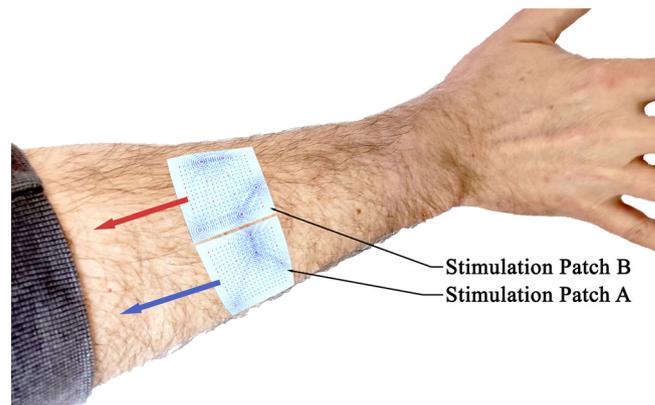


Figure 4. Distinct sensory patches

Illustrated here are two arbitrarily chosen patches of skin: A and B. In the traditional understanding, the receptors of underlying sensory cells each cover a delimited area of the skin in which they may be stimulated, comprising that cell’s ‘receptive field’ (Sherrington, 1906). The stimulations from such receptors are transduced into membrane and action potentials, which are summed and inhibited by the output of surrounding neurons, resulting in the sending (or non-sending) of a ‘signal’ to the brain. What our model seeks to add to this already well-established understanding is how completely novel constraints emerge in the interference pattern among the stimulated response of diverse nodes in their shared milieu. This emergent information is *over and above their stimulation or inhibition as it is traditionally construed*.

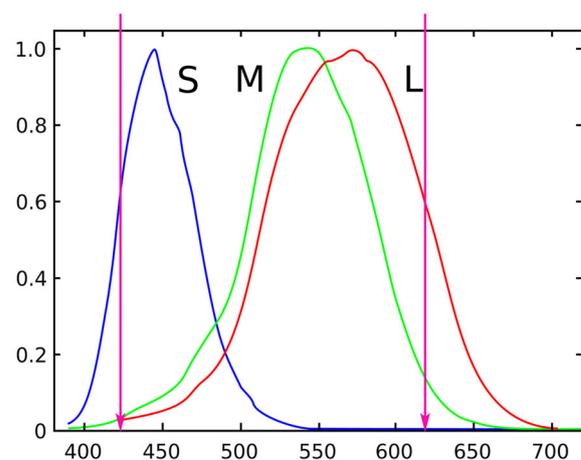


Figure 5. Magenta in trichromatic vision

Graphic adapted from:

https://commons.wikimedia.org/wiki/File:Cones_SMJ2_E.svg

of these diverse sensitivities results in the sensation of a singular phenomenon that does not objectively exist on the electromagnetic spectrum, that is, magenta. And the logic of how more fundamental phenomena – the co-stimulation of the so-called ‘red’ and ‘blue’ cones – can result in the synthetic and higher-order phenomenon of magenta can be extended to all other sensory modalities.

For the spatial mapping of the skin, we can similarly argue that each distinct patch from Fig. 4 has its own overlapping sensitivities, as illustrated in Fig. 6. For example, Fig. 6A shows an interstitial interference pattern among the 16 primary nodes, whose sensitivities are illustrated above the figure, in blue. Like the distinct populations of cones in vision, we can imagine that each of the 16 nodes also have their own bespoke sensitivities, labelled α_1 to α_{16} , in this example. (These affinities can be understood as resonant frequency, whereby α_1 to α_{16} represent the frequency at which a node will resonate the strongest. It is important to emphasize that, as illustrated in Fig. 6,

these nodes are actually responsive to a distribution of continuous frequencies that falls off exponentially, the further away from their particular resonant frequency an actual frequency is. Such resonances are examples of affinities, or sympathies.) Patch B in Fig. 6B would have a different distribution of overlapping sympathies, labelled β_1 to β_{16} . These afferent signals, as they propagate from the sense organ to the root ganglion, the spinal cord, the thalamus and on to the somatosensory cortex, will have been transduced – or *translated* in that each array of cells along the way are themselves living interpreters of patterns – through many different distributions of diversely sensitive cellular arrays. Each of these distinct cellular arrays will have its own unique distribution of sensitivities, resulting in distinct distributions *c, d, e, f*, etc. (not illustrated). Finally, these transduced patterns reach their own respective receptive fields for further translation in the sensory cortex.

Illustrated in Fig. 7A–C is an arbitrary patch of this receptive field (note that this patch of the modelled

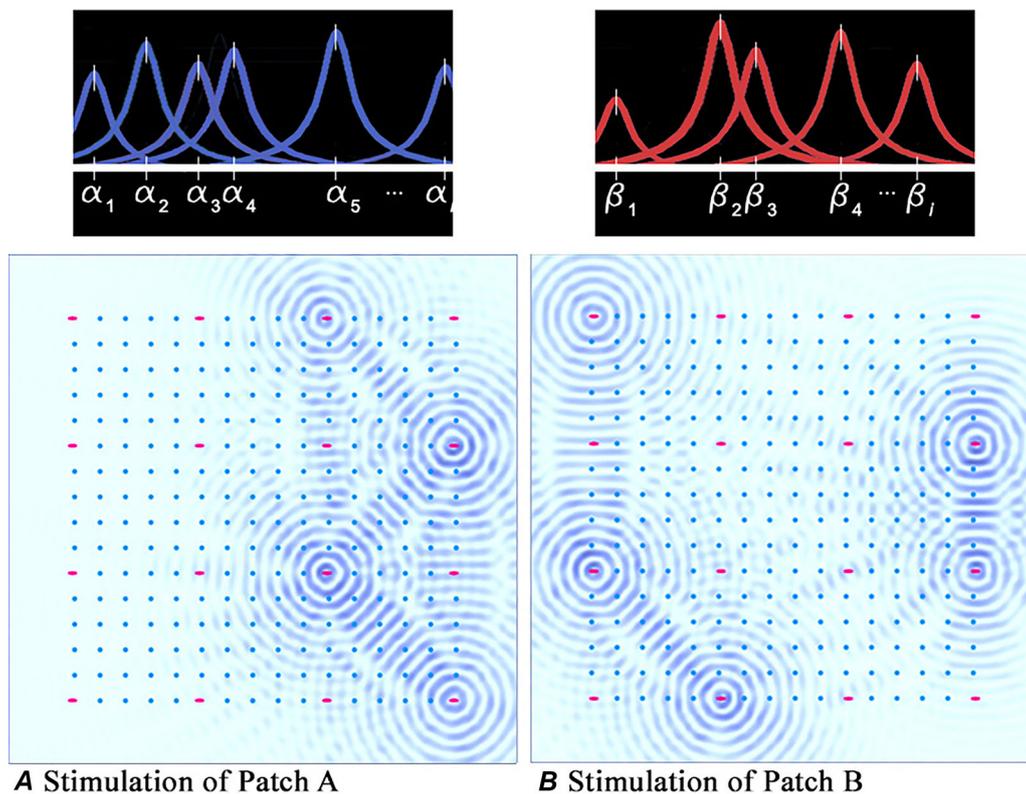


Figure 6. Discernible sensations

Any two arbitrarily designated patches – for example, patches A and B as illustrated in Fig. 4 – are distinct from each other because they have their own unique distribution of overlapping sensitivities. The transfinite potential of a continuous interference pattern both moulding and being moulded by these unique sensitivities guarantees that each patch will generate a unique and dimensionally rich pattern in response to stimulation. This pattern is then transduced through the body, gaining additional dimensional richness, as it interacts with concomitant patterns feeding into the neuraxis on its way to the cortex, resulting in a richly laminated input for information processing, as illustrated in Fig. 7.

‘cortex’ is just a partial translation of the dynamics of patches A and B at the sensory organ; there is not a one-to-one correspondence between the activity of a patch on any sensory organ and the subsequent activity on an affected patch in the cortex, given all the intermediate affinities and distributed inter-dynamics); each of the three abstract diagrams represent a self-wired circuit, each generating a unique dynamical attractor when activated. Of note is that, like any diagram of an electrical circuit, it is a static representation of a physically dynamic process of voltage and current. Similarly, Figs. 3, 6 and 7 are all static representations of constraints on a similarly dynamic circuit. And ‘circuits’ that are implemented in living beings are themselves dynamic. Basins of attraction complexify through development to do ever-more adaptive work. Given this, it is important to emphasize that the attractors in a *multistable* system, as in cybernetic models, are distinct from the kind of dynamic attractors in *metastable* systems (Hancock et al., 2023), as in the model proposed herein. To explain such *metastability*, the patch in Fig. 7 has its own unique overlapping distribution of sensitivities, here labelled γ_1 to γ_{16} . Based on these sympathies of each primary node, which are fixed for this proposed model, many distinct biases can dynamically accrue through learning, as described in Fig. 3. Proposed herein is a means of explaining how the emergence of these novel biases is the structural basis upon which a finite patch of ‘cortex’ can entail an arbitrary number of structural biases, each

of which constitutes unique higher-order affinities, in the sense of ‘Complexity’ defined above.

Figure 7A is the partial translation, or *transformation* (this term is meant as an actual biological process, which may be metaphorically understood as a Fourier transform, although even this mathematical transform is inadequate to represent all the non-linear physical processes involved in a physically realized process of transduction), of patch A on the skin as illustrated in Fig. 4, whereas Fig. 7B is the partial *transformation* of patch B; note that, for them to be meaningful, *these transformations cannot be copies of the pattern at the sensory organ*, as illustrated in Fig. 6. Throughout development, each distinct patch and its adjacencies will have become learned, or ‘mapped’. And, for the creation of a functional map, each arbitrary patch of the sensory organ is conceived, in part, by an arbitrary patch of the sensory cortex as both a distinct and inter-related dynamical ‘state’. Each sensory patch can then be touched simultaneously or in different sequences. In any case, the system is *metastable* as the stimulation of one patch on the skin, having been learned, will anticipate the adjacent patch as part of that learning. The system will thus ‘dwell’ (Hancock et al., 2023, p. 7) for a moment in one distinct attractor, while not being trapped there, as in *multistable* systems. This metastability is possible because this same ‘patch’, or matrix, is capable of both distinction and relation, *simultaneously*. In fact, for the subsequent argument regarding how these relations can become meaningful, this model illustrates how a

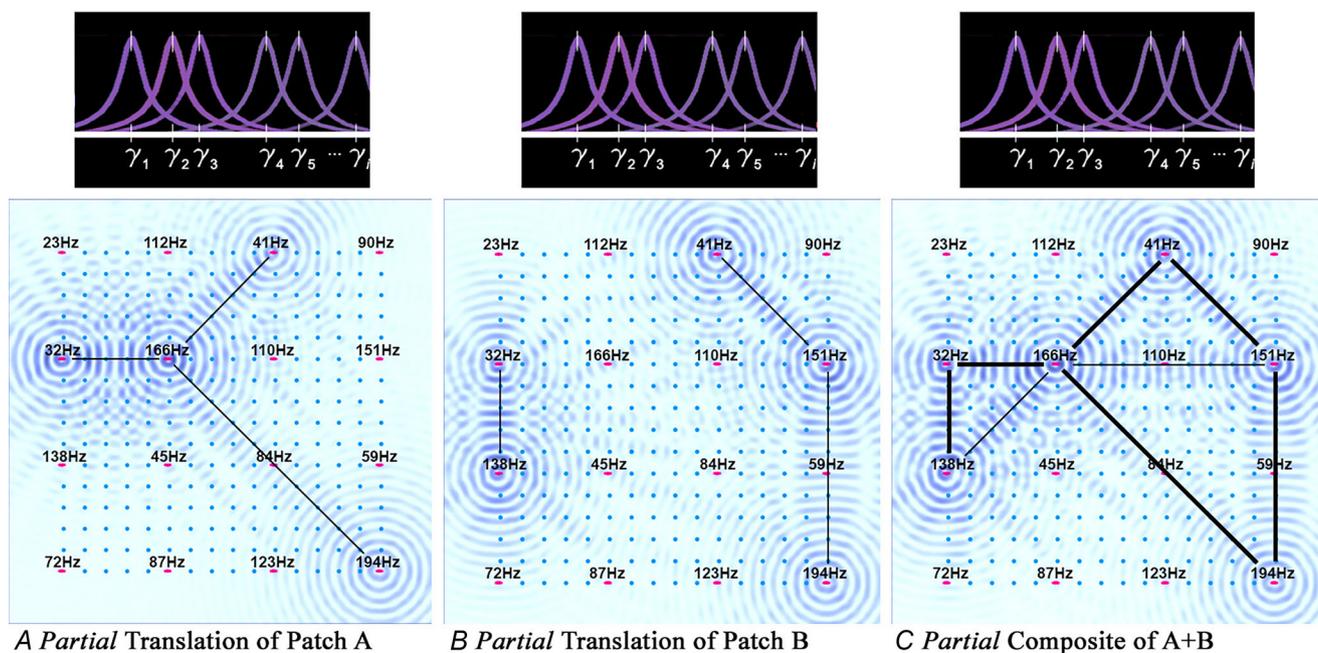


Figure 7. Discernible, yet related, sensations

Figure 6 illustrates two arbitrarily chosen patches of skin that are different, whereas in this figure, A–C each illustrates the same patch of sensory cortex. They illustrate how arbitrarily adjacent patches of skin can be associated in any arbitrary part of its wider cortical receptive field.

finite matrix, such as the patch of ‘cortex’ in Fig. 7, can embody an arbitrary number of very diverse but *relevant* patterns of patterns (and, ascendingly, patterns of patterns of patterns, enabling ever higher-order knowing and learning). For our purposes in this section on spatial mapping, this particular matrix of cortex co-constitutes the *transformation* of sensory patches A and B into higher-order, potentially relevant information for the organism.

This transformation means that the dynamical pattern at the sensory organ (Fig. 4) will be very different from the dynamics in the cortex. Nevertheless, the translated patterns will have captured and communicated the structural invariance of the originally sensed spatial organization, timing (discussed in the next section), intensity, etc. Additionally, such patterns will be superposed upon patterns, thereby ‘Complexifying’ the functionality – and thus coordinative capacity – of each developed neural structure, such as coincident sense modalities and normative feelings. These entailments are critical to meaning-making since each sensation has to be about itself, its context and its import. This novel model provides this capacity, which will be discussed further in the penultimate section. But the key takeaway for spatial mapping of touch in this section is that the biases accrued by the network array in Fig. 7 will not only recognize patch A (Fig. 7A) and B (Fig. 7B) as distinct entities – analogous to the phenomena of red and blue – but also the composite A+B (Fig. 7C) – analogous to the phenomenon of magenta. Furthermore, this nested logic of simultaneously distinct and interrelated dynamical attractors can grow to arbitrary levels of ‘Complex’ coordination.

Based on this model so far, it is argued that, throughout an animal’s development, it will have instantiated network biases for *both* each patch on their body *and* their adjacent relations, insofar as adjacent patches will be co-stimulated through development. Thus, because of the very high dimensionality of these networks given the astronomical number of configurations possible, an entire body map, in principle, can be superposed in a rather compact finite matrix of cortex.

This high dimensionality can be illustrated with a conservative estimate of a three-dimensional matrix of primary nodes, for example, $4 \times 4 \times 4$, resulting in 64 unique primary nodes. Given 32 non-directional connections, or edges, between these 64 nodes, there exists (per ‘ n choose r ’) over 1.83×10^{18} different possible configurations of 32 connections. This is already an astronomical configuration space, although finite. Add to this, however, that this model proposes a continuous interstitial medium able to manifest an interference pattern among these diversely tuned nodes. This pattern is the result of the independent and continuous parameters of frequency and phase, which effectively renders the

proposed possibility space of this simple matrix *transfinite* (Cantor, 1955), that is, a bounded – *while actual* – infinity of possible patterns.

Given this high dimensionality, an entire body map can be developed through self-stimulation. Furthermore, the dynamics of the sensory cortex network are *metastable*. As such, given the hierarchically ‘Complex’ nesting of patterns of patterns, touching one patch on the body can prime the stimulation of previously constituted network configurations that represent adjacent patches in the sensory cortex. This priming is a kind of *anticipation* – that is, the generation of a conceptual map whereby the spatial map of the body’s surface is transformed, in the mathematical sense, into a configuration space with biodynamic implications. This configuration space, which is both finite and metastable, has more than enough degrees of freedom to embody both arbitrarily numerous distinct patterns *and* their inter-relations, simultaneously.

Similarly, Fig. 7, as a model, can be extended to other modalities. For example, auditory ‘space’ can be similarly configured. C Major and E Minor, along with their inter-relation, C Major 7th, can likewise be represented in a finite and metastable matrix. The same is true for colour space, as the distinct retinal configurations are translated by the visual cortex as the phenomena of red and blue, while their co-occurrence is instantiated via the higher-dimensional biases that anticipate magenta. It is notable that in all of these cases, there is no need to occlude the lower ‘Complexity’ pattern. This is all possible because of the unimaginably high dimensionality of the proposed model, in terms of both actual connections among nodes and the virtual connections potentiated via phasic alignment of the continual interference pattern within the relevant noise. The ability to harness the sparse order of the *virtual* via the *actual* is only possible because of the continuous interstitial medium that both moulds and is simultaneously moulded by the activity of nodes.

And it is this last capacity that rescues life from endless possible dead ends, that is, local minima. In response to the disparation of different wavelengths of light, dissonant chords and disparate spatial sensations, it is the continual harnessing of these radically emergent degrees of freedom that affords the scaffold allowing life to develop into ever more ‘Complex’ patterns. Nevertheless, it is also the reason why feedback in living systems is never completely a closed loop in a functional sense. And neither is it algorithmically closed with a dash of stochasticity, as in many contemporary cybernetic models. There are, and must be, dynamical attractors that habituate the fruits of disparation, viz. the harnessing of relevant order in the interference patterns or noise. But this continual harnessing of novel constraints means that the initial and boundary conditions will always be adrift in living systems. But this drift, due to the noise, is a *relevant* noise because of the system’s intrinsic affinities, which can and

must always be open to the indeterminate outcomes of their open systems.

Given this point, the observation by Bernstein, Tuthill and Wilson that cyclical movements in living beings never exactly repeat themselves makes not just stochastic but generative and adaptive sense. As living systems continuously reform themselves in order to inform themselves, the initial and boundary conditions of the system are never the same twice (Noble, 2022a, p. 5173), and such conditions are the scaffold for the accretion of ever novel dimensions and constraints on subsequent dynamics (Longo & Montévil, 2014, p. 187; Simondon, 2020, pp., 9, 694, 711). And, perhaps surprisingly, this radical generativity is the basis for *equifinality*. In other words, the other aspect of Bernstein's observation is that the blacksmith can still hit the same functional area in spite of ongoing fatigue, destabilization of one's footing or any number of other indeterminate perturbations. But to really appreciate this seemingly paradoxical aspect of coordination, we need to explore timing via phasic inter-relations.

Coordination in time (via phase)

To rigorously make the case for Bernstein's observations regarding the consistency of our behavioural outcomes, even as these behaviours never exactly repeat, the case for coordinated timing must be integrated with that of spatial coordination, as introduced above. This section will deepen the above model by exploring phasic chemistry at the molecular scale to explain the spatiotemporal integration observed at the intercellular and organismic scales. More precisely, this novel model posits that the phenomenon of *phase* operates inside the cytoplasmic milieu of each cell and constitutes the actual capacity for self-resolution of many diverse modal inputs, which results in the ostensibly singular and adaptive actions that are observable at higher scales.

Saigusa and colleagues' work on amoebae helps make the case for spatiotemporal integration via phasic relations in cellular cytoplasm. In studying the response of a population of single-celled amoebae, *Physarum polycephalum*, in response to external perturbations over a 60-min period, they were able to observe that a significant proportion of the population seemed to learn the periodicity of these perturbations (Saigusa et al., 2008). Their study imposed a dry, cold shock on this population every 60 min three times, the first shock being at 120 min. They found that on what would have been the fourth shock at 300 min, many of the single-celled organisms slowed down, apparently in anticipation of this fourth shock that never occurred. As the external perturbation ceased, this ostensible anticipation occurred a few more times before the population resumed its normal foraging

patterns. Then, at 600 min, a single dry cold shock was again administered. Tellingly, at 660 min, a significant portion of the population again slowed down even though no shock was given.

In order to explain this apparent 'ability to memorize the periodicity' (Saigusa et al., 2008, p. 8), they leveraged the Kuramoto (1984) model of weakly coupled chemical oscillators to hypothesize how amoebae could have internalized an arbitrary external pattern so that they might coordinate their behaviour with their environment in time. To summarize, this model involves a large population of loosely coupled and diversely tuned chemical oscillators that would interact within each individual cell. The phases of these oscillators would initially be independent of each other, that is 'randomly' distributed with respect to each other. However, upon periodic perturbation, the phases of chemical oscillators, whose resonant frequency is at or near the perturbation period, would begin to align. Saigusa et al. then argue that these groupings of similarly tuned oscillators – whose phases have aligned – can now group with other groups of aligned oscillators; now we have groups of groups of aligned phases. It is hypothesized that when the external perturbations stop, the groups of groups will dissipate, whereas the initial groups of distinct oscillators will remain aligned. Ostensibly, it was the groups of groups that were required to change the behaviour of the amoebae, internally motivating them to slow down spontaneously in anticipation of the internalized periodic perturbation. But, when enough time passed, these groups of groups dispersed, and spontaneous anticipation ceased. Nevertheless, when the lone perturbation was initiated at 600 min, there still existed a kind of 'memory' in the groups of individual oscillators that remained phasically aligned. This remaining layer of organization could then be quickly leveraged to modify subsequent behaviour in amoebae. But how can this model be employed to explain timing, and ultimately coordination, in living organisms generally?

Moving back into the multicellular realm of organisms with nervous systems, we can posit that the timing capacities described by Kuramoto, Saigusa and others (Strogatz, 2000) are inherent in cell cytoplasm across the phylogenetic tree. If this is the case, this intrinsic and flexible timing capacity can certainly be attributed also to neurons, even in the absence of brains. These diversely tuned oscillators afford such cells two key attributes: (1) the unique sensitivities of each cell (the first attribute of the model in the previous section) and (2) the relationship of those cells to the activities of the larger multicellular milieu (the second attribute of the model above).

Genetically, this first attribute is the phenotype of a given cell that is partly expressed by the specific nature of the chemical oscillators its Hodgkin cycles will facilitate (Noble, 2022a, p. 5173). The second key

attribute is that this distinct distribution of sensitivities will be the means by which each cell responds, or not, to its interstitial milieu to amplify novel, higher-order dimensions harnessed from beat frequencies, constructive interferences and similar phenomena in the distributed regional electromagnetic milieu (Hales, 2014). This milieu will exhibit – like an *in vivo* analogue Fourier transform – a particular frequency and phasic character that both moulds and is moulded by the distinct sensitivities of each cell, *simultaneously*, exhibiting Noble's (2012) biological relativity.

From the point of view of the particular cell, as with the model proposed by Saigusa et al., the distributed milieu will perturb the cell and thereby cause some chemical oscillators to align physically. In the model proposed in this section, it will be the higher-dimensional components of the cellular milieu's interference pattern that constitute such perturbations, for example beat frequencies and constructive interference. In this way, again as in Saigusa et al., the cellular cytoplasm will internalize ephemeral aspects of the shared interstitial cellular milieu insofar as they can cause the phases of select chemical oscillators to align. Once aligned, this oscillatory alignment can affect the firing of that neuron, which affects the interstitial milieu, again, as each dynamic at diverse scales affects one another, *simultaneously*.

It is important to bear this last caveat in mind, since the more ubiquitous conception of a sequential stepwise cycle or circuit will not achieve the 'Complex' coordinative capacities extant in living systems. This is, in part, because such a stepwise process cannot resolve the paradoxes of simultaneity that life must continually resolve, such as part *versus* whole; large *versus* small scale; now *versus* then; individual *versus* collective; and many more. Noble (2022a, p. 5174) makes this same point, arguing that 'The [stepwise] cycle is therefore a simultaneously active ring, not a one-way cycle'. On the same page, Noble continues:

Causation is formed at the same time by molecular dynamics (channel gating and ion movement) and the structural constraints from history (initial conditions) and boundaries (constraints by structure). There is no one-way around the cycle. It all happens simultaneously. Contextual and dynamic causes are inextricably intertwined. ... Between each of these levels, the upward and downward forms of causation must be simultaneous, so forming rings rather than cycles of interaction. Those causal rings are the basis of living systems.

Subsequently, the phasic alignment of sympathetic cytoplasmic oscillators is affected by the more distributed and pervasive forms of the multicellular scale field, which is simultaneously energized by neuronal action potentials, which are simultaneously of 'channel gating and ion movement' and of the alignment of cytoplasmic oscillators. Each aspect of energy/matter co-constrains

the other as they co-emerge. One way to think of this emergent 'ring' is a co-constituted dynamic that sustains itself for some time. It may be a relatively fleeting and ephemeral dynamic, but aspects of its asymmetric topology may be offloaded onto more inertial cellular structures (the third attribute in the previous section), such as so-called 'hard-wired' synaptic connections.

The proposed heuristic model proposes something similar to Fig. 8 in order to explain how more ephemeral asymmetric patterns can be accreted by more inertial structures. It is important to note that empirically observed spike timing dependent plasticity (STDP) has a timing window outside of which firing timing is not offloaded; the time difference must neither be too long nor too short. For example, 'STDP is highly sensitive to the interval between the pre- and postsynaptic spikes; however, the role of STDP in generating timed responses remains unclear. If a presynaptic spike consistently occurs 25 ms before the postsynaptic spike, the synaptic strength between the two neurons will increase' (Buonomano & Carvalho 2009, p. 268). This requires a rather precise means for cells to discern timing. The proposed model accomplishes this by having interstitial bodies – whether, for example, glial cells or particular structures in a cell membrane – between two firing cells. As these two cells – P1 and P2 in Fig. 8 – fire, their pulse – red and blue, respectively – will travel in the interstitial gap. The purple wave is their superposed sum, such that, when they constructively interfere, the constructively heightened pulse will affect the nearest interstitial body greater than the others. In a biological context, this could – especially given a relativity stable 'ring' dynamic – create a chemical gradient whose resultant asymmetry between them will establish directionality for subsequent dendritic budding.

Also contributing to directionality, given how densely organized neurons actually are, is the idea that a dynamic 'ring' attractor will generate asymmetric potential terrains between neural membranes. If the topography of the global field potential has a causal feature that affects local channel activity (Hales, 2014), not only might it induce dendritic budding, but any asymmetry in that field will anticipate which cell will be the circuit sink and which will be the source, thereby establishing directionality.

Once directionality can be instantiated in the network, both spatial and temporal information can be established. In addition, given the capacity for these models to incorporate inter-relations among dynamic affinities, entirely distinct types of qualitative information can be embodied, from colours to sounds to higher-order conceptions of adjacency. With the addition of timing, Fig. 7C can be modified as in Fig. 9.

There is a very large and growing body of neuroscientific evidence to be brought to bear on the development of this heuristic model. Of particular interest moving forward will be empirical and mathematical

models that employ concepts of synchrony (McMillen & Kopell, 2003), coupled oscillators (Medvedev et al., 2003), ‘leaky oscillators’ (Cannon & Kopell, 2015) and ‘ring oscillators’ (Andrzejak & Espinosa, 2023; Lee & Krischer, 2023).

It is important to remember that this one array of networks is metastable, meaning that it has any number of possible distinct, while also interrelated, network dynamics. The configuration illustrated in Fig. 9 is just one possible attractor that entails at least two lower-dimensional networks as in Fig. 7. An average neuron, for example, can be connected to 10,000 other neurons (Kull & Favareau, 2022, p. 19). Figure 9 shows a node with a maximum of five connections. With each node having 10,000 possible other connections, the possible configurations are astronomical. Given this huge configuration, or possibility, space, it is possible to imagine how arbitrarily many configurations can accrue throughout the lifetime of an organism.

As an infant human touches itself and others and manipulates objects seemingly at random, it is developing stereotypic coordinative behaviours as illustrated in the models above (see also Bressler & Kelso, 2016; Kelso, 1995, 2012; Tognoli & Kelso, 2014; Tognoli et al., 2020). Countless impromptu ‘experiments’ are run. For example, the infant’s grasp of a mother’s finger becomes a stereotypic gesture as the child is rewarded with human contact having manipulated its muscles in just such a way. This behaviour might then be used to grab a block that goes in the mouth, the entire somatosensory experience being instantiated in the sensory and motor cortices. Later, these stereotypic behaviours are adapted for getting food in the mouth. In this way, an entire

vocabulary of spatio-temporal muscular coordination can be instantiated in these networks, each able to be superposed with the other at will to develop into a rich, corporeal ecosystem of coordination.

Given the current popularity of cybernetic logic, such as the stepwise iterations of algorithms and injections of randomness in the development of learning models, it may be tempting to assume that the same kind of logic holds for the intrinsic development of an organism’s capacity to coordinate itself. Building off the non-cybernetic logic of previous sections, however, the next section will continue to make the case for a third way, which suggests how numerous acquired behaviours can be modified, integrated and actualized into novel and contextually relevant ‘Complex’ behaviours.

Semiotics in coordination

Having now presented the general logic of our model on the cellular and intercellular level, it is imperative that we move up to discuss the importance of such dynamics on the organismic level. It is here that we see where the model is attempting to explain something that many systems-theoretical models do not, in our opinion, satisfactorily explain: the centrality of *semiosis*, or the centrality of sign-mediated relationships, in both the internal organization and the external interactions of organisms.

The ability to harness the sparse order in the *virtual* – the set of circumstances from whence nascent asymmetries, or constraints, may emerge and be habituated – by the co-extensive operations of the *actual* is the defining characteristic of sign-use by living beings

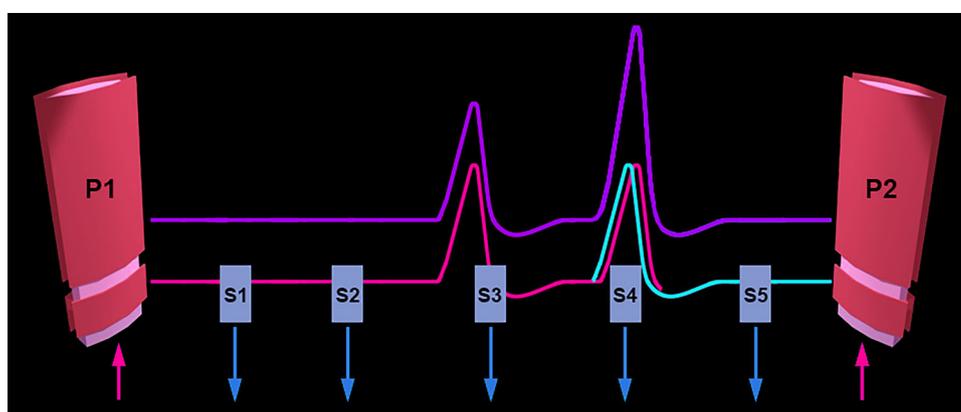


Figure 8. Discerning firing timing between nodes

Nodes P1 and P2 represent the darker nodes in Fig. 3, whereas the smaller nodes S1–S5 represent the more numerous grey nodes. The lower pulse on the left emanates from P1, while the lower pulse on the right emanates from P2. The upper wave is the superposed sum of these two pulses and is meant to represent a section through the interference pattern illustrated in Figs 3–7 and 9. Secondary node S4 will be able to register a greater potential pulse than nodes S1–S3 and S5. This asymmetry not only illustrates how timing can be discerned between the two emanations from P1 and P2, but it also illustrates how the geometry of the interference pattern can be discerned, insofar as the summed pulse can emerge above the noise floor.

disparation (Simondon, 2020, p. 711) results in (2) *relevant noise* from which novel constraints are harnessed, and (3) explaining how these novel constraints result in a *basin of attraction* (Kauffman, 1993, p. 176), towards which multiple stereotypic behaviours modify, integrate and actualize themselves via an action–perception loop into a unified behaviour.

In the first step, in the context of thirst and the desire for a glass of water within reach, the model above posits that the integrated networks of perception and action will be primed for reaching out to that glass. More specifically, the current state of the body (and all of its embodied semiotic associations) will be felt, and the anticipation of having grasped the glass (and all of its embodied semiotic associations) will simultaneously be evoked, having proven previously to have resulted in a successful interaction with the world. Now there are at least two broad domains of sign-use in the networks at play here: the state of the body as it is at the current moment and the anticipatory states (via re-entrance, reafference, readiness potentials, etc.) that it assumes in its orientation towards the possibilities of immediate next action (and as influenced heavily by its history of similar interactions in the past) (cf. Rosen, 1985). As illustrated above in Fig. 7, two lower-dimensional patterns can be superposed to elicit novel dimensions, or constraints, in the interstitial field to create a higher-dimensional pattern that entails both the lower-dimensional patterns and their novel dimensions. But, after having been habituated via structural biases, these novel dimensions can work in reverse: as in pattern completion (Carrillo-Reid et al., 2021; Mishra et al., 2016), the partial stimulation of the higher-dimensional pattern can evoke ‘missing’, or sympathetic, patterns.

Similarly, the sensation of both the current state of the body and the anticipation of having grasped the glass will evoke adjacent patterns. Crucially, from a repository of innumerable possible patterns in a developed organism, the relevant patterns are near-instantly evoked because of the very specific sympathetic constraints provided by the priming patterns. These sympathies, or physical resonances, create a literal *affinity* for the *relevant similar patterns* insofar as they are co-constrained by these two disparate states, among other contextual cues. Doing so, in turn, will further populate the relevant thalamic and cortical networks with contextually relevant patterns. This inexorable process of attraction is possible because any number of stereotypic behaviours and associated motor schema – each with their own ‘Complex’ of potential affinities accreted through learning and development – will be selectively stimulated via something akin to pattern completion suggested above. In other words, the *disparation* posed above – the desire to grasp an available glass of water – tends to conjure patterns that are not the

initial sources of *disparation*, like the tacit knowledge of the next word and/or notes in a familiar song.

In the second step we outlined above, this accretion of arbitrary numbers of patterns, even if potentially relevant to the task at hand, would seem to exacerbate the ability to cohere upon a singular behaviour of reaching out. Nevertheless, as per the heuristic model above, it is hypothesized that the resultant *noise* – that is, the result of these patterns’ superposition, or *disparation* – is necessary. The phenomenon of *disparation* can be understood via the example of binocular vision: Simondon describes ‘in the case of binocular perception, the *disparation* of monocular images is what renders them incompatible. However, it is precisely this degree of *disparation* that is taken as a positive index of the relative distance of fields in three-dimensional perception. Thus, knowledge advances by positivizing incompatibilities’ (Simondon, 2020, p. 711). But, instead of these ‘incompatibilities’ being random noise, it would be *relevant noise*. It would be noise in the sense that the interstitial common medium would be replete with innumerable independent signals, which is technically noise. Nevertheless, it would be *relevant noise* in that these signals, although independent of each other, are intrinsically the result of the dynamical ‘rings’, as discussed above. Insofar as some of these signals constructively interfere with each other or generate legible beat frequencies able to cause phasic alignment in the chemical oscillators, then some sparse signals, or ‘order’, can be harvested from the noise. It is exactly because of the asymmetries in this relevant noise that novel, and relevant, dimensions are made available to the system itself.

Having amplified these novel dimensions such that they are expressed via burst frequencies of action potentials, they can mould the interstitial field accordingly. The expression of these higher-order dimensions can be thought of as a higher-dimensional *complex order parameter* (Kuramoto, 1984, p. 71; Strogatz, 2000, p. 3). However, instead of just being a mathematical representation of the degree to which a group of oscillators have aligned, this higher-dimensional pattern can exert downwards causal influence, in the sense of an Aristotelian *formal cause* – which is to say that such higher-order patterns now themselves constitute *basins of attraction* influencing subsequent activity. But even provided the means of attraction, the question remains: how are multiple, initially unintegrated and disparate, stereotypic behaviours – having been evoked due to their current relevance – integrated into one continuously unified, coordinated and often ‘Complex’ behaviour?

For this, our third step, the action–perception cycle of the early 20th-century physiologist Jakob von Uexküll (1926) will be used to describe how the *basin of attraction* aids in coordinating multiple stereotypic behaviours and how they co-emerge in a real-time application. Figure 10

is Jakob von Uexküll's *functional circle*. It posits that the organism's 'World as sensed' and the organism's 'World of action' work together to manifest what is indicated as meaningful and actions appropriate to that signification. The important point to make for this section is that Uexküll posited the manifestation of what we now call an *effERENCE COPY* (denoted in the diagram here as the 'New Circle'), which is sent from the motor cortex back to the sensory cortex (cf. Hoffmeyer, 2001, 2004; Kull, 1998). (Grüsser argues that the lineage of the *effERENCE COPY* concept, also more commonly referred to as the *refference principle*, starts with Jakob von Uexküll (Grüsser, 1995, p. 47). Erich von Holst also did some related empirical work on *refference* (1954); see also von Holst's work on 'superposition and attunement' (1939, p. 266) and his studies on dominant coordinating rhythms in animal physiology (1939, p. 167).) This *effERENCE COPY* establishes an expectation of what the animal anticipates happening, given its actions. If what is perceived is the same as the *effERENCE COPY*, then the animal maintains the action. If, however, something has happened in the interim, an updated action is initiated, traditionally conceived as 'feedback control'. What we need to add to this model now is a way of explaining how such precisely attuned to the moment 'feedback control' arises out of innumerable competing available reactions.

For example, upon perception of the glass of water, the mind of the thirsty subject will have evoked numerous *relevant but disparate* stereotypic behaviours, manifested as dynamical network attractors discussed above. Multiple simultaneous attractors superpose creating their own bespoke *disparation*, an aspect of which is an interference pattern, from which novel higher-dimensional variables will be harnessed. It is supposed that this embodied composite conception of the body's current and desired state is passed on to the motor cortex from other cortico-thalamic networks where the stereotypic dynamics have been accreted. Once in the motor cortex, there is perhaps a 'first draft' of coordination, whereby the latent stereotypic behaviour most closely sympathetic

to this higher-order *disparation* is conjured. This draft entails the feedback from the *effERENCE COPY* to instantiate the *basin of attraction* that emerges from the novel dimensions – now dynamical constraints – harnessed from the *disparation* of *all* the superposed networks accreted along the way to the motor cortex.

This *basin of attraction* is more than an 'expectation' as it is an ever-developing cypher – intended in the figural sense, like a beguiling character in a play whose ostensibly mercurial behaviour both moulds and is moulded by the fate of all the other actors' exchanges, *simultaneously* – that *actively* bends, attracts and constrains the dynamics of the stereotypic behaviours *both* towards each other *and* the overarching goal, *simultaneously*. It does this in an inexorably adaptive way both because of the (bottom-up) overlapping sympathies discussed in the previous section and the (top-down) coordinative capacity of the emergent *complex order parameter* discussed above. Adaptive multistability (and semiosis) are possible because the nascent sympathies that exist in the overlaps between each disparate dynamic at their lower levels of dimensional 'Complexity' can constructively interfere, generating a higher-dimensional index. This index – the embodied *order parameter* – actively constrains disparate dynamics towards a common denominator that is the asymmetric results of the disparate dynamics themselves. A beat frequency, for example, is the frequency whereby disparate frequencies and phases align. Those aspects of each disparate lower-order dynamic that resonate and generate a legible beat frequency will be the aspects that can constrain their respective dynamics so that they tend towards each other. Their disorder, that is increase in entropy, is the pre-requisite by which entropy can be reduced so that mutual information may be increased – not in spite of all the disparate degrees of freedom, but because of them.

The initial 'first draft' in the motor cortex will have allowed greater degrees of freedom for each disparate dynamic, such as the stereotypic behaviours. But once the *effERENCE COPY* has been passed back to the sensory cortex – informing the *basin of attraction* – it will serve 'as a skeleton' (Uexküll, 1926, p. 157), or, more precisely, adaptive constraints, by which subsequent 'drafts' of the coordinated behaviour are more refined, or *concretized* (*sensu* Simondon (2017, p. 25)). This process of *concretization* is the real-time and non-random weaving together of distinct and initially disparate – while also relevant to the task at hand – stereotypic patterns. This remains the case even as novel perturbations affect the organism mid-behaviour, as illustrated in the work of Bernstein and Saigusa et al., discussed above. And, again, this *basin of attraction*, even though it is a kind of coordinating force and continually perturbed by its *effERENCE COPY*, is neither strictly top-down nor bottom-up, as Noble (2022a, p. 5174) argues: 'the upward and

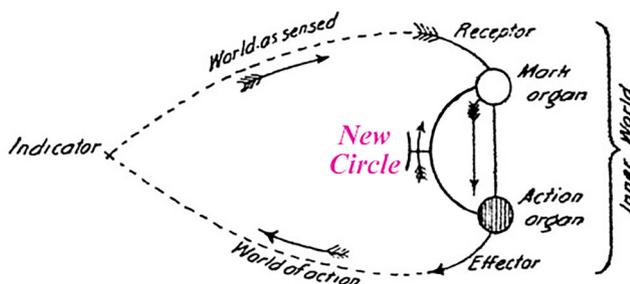


Figure 10. Jakob von Uexküll's functional circle
Adapted from his *Theoretical Biology* (1926, p. 157).

downward forms of causation must be simultaneous'. This *biological relativism* is a necessary pre-condition for the coordinating constraint, or ever-developing *basing of attraction*, which is itself a 'Complex' dynamic with inter-related qualities, qualities that are the composite result of many formerly disparate patterns. Each dynamic is tuned, based on distinct, overlapping sympathies, to flow into the others, all based on the sparse emergent order harnessed from within their shared *relevant noise*.

Conclusion

Here we have argued that *relevant noise* is the necessary operational counterpoint of the more inertial, although no less necessary, structure that emerges in living systems to bias subsequent dynamics. One of the central claims of this paper is that, in this dynamical process, one of the attributes that renders the resultant tension between *relevant noise* and habitual structures adaptive is the development of diverse overlapping affinities in the chemical and cellular networks. And how these overlapping sympathies can resolve this tension between the distributed, transfinite *potential of relevant noise* and localized, finite *actuality* of structure is the continuous common medium that both moulds and is moulded by the transductive, or informational, exchange among all these layers of asymmetric processes, simultaneously.

In considering this novel model and its implications, it is tempting to fall back on our legacy mechanical metaphors. Nevertheless, in the pursuit of understanding extant physiological coordination, we can resist the stepwise misunderstanding of the above conception. It is a legacy attribute of written language that we must put these attributes and their inter-dynamics in a sequential order. However, this is not necessarily how dynamical systems actually *are*. Again, as Noble (2022a, pp., 5173) notes: 'We should not be confused by the fact that we have to use finite steps to perform the integration into thinking that this represents reality... Everything computed in each step can be regarded as [merely] an approximation to [its] true simultaneity'. Of course, there are stepwise aspects to these processual operations. But, just as there is no mass without gravity, and gravity without mass, the novel dimensions that emerge in living systems to irreversibly alter initial and boundary conditions at each infinitesimal moment are characteristic of a physical system that is both distributed and local, ephemeral and inertial, transfinite and finite, *simultaneously*. It is because of these attributes that physiological coordination in living systems can be explained by the harnessing of ever-novel dimensions within the *relevant noise* via the large population of reactive nodes with diverse affinities for their shared milieu, as exemplified by the primary nodes in the section 'Coordination in space' or chemical oscillators in the section 'Coordination in time (via phase)'.

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Additional information

Competing interests

Neither author has any competing interests to declare.

Author contributions

J.A.B. is responsible for the proposed heuristic model and its application to coordinative dynamics in living systems. D.F. contributed expertise in relating the application of this model to the discipline of biosemiotics, especially in the introduction and the section ‘Semiotics in coordination’. Both authors have read and approved the final version of this manuscript and agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. All persons designated as authors qualify for authorship, and all those who qualify for authorship are listed.

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chemical oscillators, continuity, coordination, phasic alignment, relevant noise, simultaneity, sparse order, superposition

Supporting information

Additional supporting information can be found online in the Supporting Information section at the end of the HTML view of the article. Supporting information files available:

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