The Complementary Nature of Coordination Dynamics: Self-organization and Agency

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Twenty years of empirical and theoretical research has demonstrated that basic forms of biological coordination arise and change due to self-organizing synergetic processes. Here we suggest, using facts and ideas from brain research and quantum measurement theory, that metastability in the underlying coordination dynamics is crucial for the creation and annihilation of meaningful information. Such information may then be used to guide, modify and direct the activities of an organism.

Key words: coordination dynamics, self-organization, broken symmetry, metastability, meaningful information; agency

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"Things come together in this world to make things happen, that's all you can say. They come together."

1 Introduction

In this brief essay, I wish to discuss an elementary law of coordination the original form of which arose out of a wonderful collaboration with Hermann Haken that began twenty years ago. In that research, the synergetic concepts of self-organization and the mathematical tools of nonlinear dynamical systems were used to model observations of cooperative phenomena and spontaneous phase transitions in biological coordination [8], [13]. This work has spawned a broader research program dealing with coordinative phenomena in the brain, cognitive, social, behavioral and economic sciences (e.g., [1], [11], [16], [17]).

My purpose here, however, is not to go into all the details surrounding the law and its derivation, nor to survey the evidence that has accrued in its favor (see [7], [14] for reviews). Nor will I describe the numerous elaborations and extensions - both empirical and theoretical - that have come to pass and are now referred to in the literature as "coordination dynamics". Instead, I wish to delve into what this elementary law might mean for understanding the coordination of living things. In particular, I want to suggest an interpretation that provides an inroad into the origins and creation of (meaningful) information. Such meaningful information once stabilized in memory may then be used to guide, modify and direct the activities of an organism. Put another way, the goal is to unite, in a single framework and with no resort to vitalism, the spontaneous self-organizing nature of coordination inspired by Haken's synergetics, and the obviously directed, agent-like properties characteristic of animate nature. In fact, I want to suggest that the former (self-organization without the self) when construed in a proper light and coupled to certain other facts and ideas, provides a natural foundation for the latter.

Turning to the quotation from Graham Swift's Booker Prize winning novel "Last Orders", how do things come together, and when they do, what's the nature of the coordination? Coordination is not just matter in motion. It is a kind of functional order or pattern in both space and time that is adjusted flexibly to changing circumstances. Many different kinds of coordination are possible in Nature, and certainly not all are understood. Following the behavioral physiologist, Erich von Holst [9] who spent his life studying coordination in a wide variety of creatures - from worms to men - we can imagine at least three basic types: absolute coordination, in which component parts are locked together in time (like the synchronized flashing of fireflies, a couple making love or phase synchrony between parts of the brain); partial or relative coordination, in which the component parts 'lock in' only transiently and then break apart as circumstances change (like a little boy walking hand in hand with his father on the beach; dad must slow down and/or son add a step so that they can stay together); and no coordination at all, in which the component parts behave quite independently (as occurs in the locomotion of millipedes and centipedes when the same little boy chops of their middle legs, or perhaps after persistent, long term practice in playing the piano or the violin). Various blends, mixes and transitions between these coordinated behaviors are also possible in order to match the exigencies of the internal and external environment. It would be nice if science could parsimoniously account for all these different kinds of coordinated behavior.

Now obviously, says the skeptic, the details of coordination are bound to be very different at different levels of biological organization, for different organisms and for different functions. What makes one think that any kind of common underlying principle exists? The reason is that a number of basic coordination phenomena exist that seem to cut across a wide range of levels, creatures and functions. Nature, as the saying goes, operates with ancient themes. Among these (experimentally-verified) phenomena are: patterned states of coordination that remain stable in time despite perturbations; the ease with which component parts and processes can be flexibly engaged and disengaged as functional demands or environmental conditions change; the existence of multiple coordination states - so-called multifunctionality - that effectively satisfy the same set of circumstances; the selection of particular coordination patterns that are exquisitely tailored to suit the current needs of the organism; adaptation of coordination to changing internal and external contingencies; abrupt transitions from one coordinated pattern to another; transitions from partially to fully coordinated states and vice-versa; remaining in the same coordinated pattern even when conditions change (a kind of memory), and so forth. Such phenomena appear so commonly and so consistently in Nature as to suggest the existence of an underlying lawfulness or regularity that transcends the multitude of differences.

In its most general form the coordination law takes the following form:

$$\dot{\phi} = f(\phi, k, noise) \tag{1}$$

In words, the rate of change of a variable called phi (ϕ) - phi with a dot on top - is a (in general, nonlinear) function f of how phi is affected by parameters, k, and noise (since all real systems are noisy and contain fluctuations). The above formulation will be familiar to all practitioners of synergetics [6].

In every scientific field, the choice of key variables must be based on empirical insights: coordination variables define stable and reproducible relationships among interacting components. In this case, the relative phase, phi has proven itself capable of capturing patterns of coordination among many different kinds of things at many different levels, from individual neurons, to neural groups or ensembles, to different brain regions, even to cognitive function itself. However, although the same coordination phenomena may exist at different levels, the first step is to find dynamic laws within a level. The main idea is that understanding at any level of organization requires knowledge of the control parameters, the interacting components themselves, and the patterns of coordination that emerge from component interactions.

Fundamentally, the problem of coordination deals with how the parts and ongoing processes of any system - at any level of description - come together to form coherent patterns of behavior. Coming apart and getting together in time is inherent to animate form. Processes go up and down, back and forth. They have a rhythm to them. Oscillation or rhythm is the cornerstone of life, of everything that isn't dead, of all systems that are not at equilibrium. Although rhythmical behaviors can be quite complicated, we have the deep impression that the principles underlying them possess a beautiful simplicity. Rhythms are known to confer positive functional advantages for the organism. Among these are spatial and temporal organization, prediction of events, energetic efficiency, and precision of control. For present purposes we restrict our considerations to the simplest case of coordination, the interaction between only two rhythmical active components. The equation can easily be - and has been - extended to the treatment of multiple interacting components (e.g. [21], [29], [30], [23]). The specific form of the coordination law is as follows:

$$\dot{\phi} = \delta\omega - a\sin\phi - 2b\sin 2\phi + \sqrt{Q}\xi_t \qquad (2)$$

Briefly, Eq (2) contains essentially three kinds of parameters: one that reflects asymmetries or heterogeneity between the interacting components ($\delta\omega$); one that reflects external or internal factors (control parameters) the ratio of which (b/a) has been shown to govern the strength of coupling between the components; and a term for noise or fluctuations (ξ_t) of a given strength Q that gives rise to phase variability [28]. This law 'wraps up' or 'enfolds' in a single equation all the neural and mechanical properties that give rise to certain coordinative phenomena in both brain and behavior (e.g., [10], [20], [25]). The dynamics (Eq. 2) have also been shown to capture coordinative relations between: a) components of an organism; b) organisms themselves; and c) organisms and their environment ([14] Chs. 3 and 4 for review), attesting to their universality [7].

The original form of the equation, known in the literature as the Haken-Kelso-Bunz (HKB) model assumed identical components ($\delta\omega = 0$) and therefore symmetry of the coordination dynamics [8]. The HKB model was able to account for Kelso's [12], [13] observations of bistability in bimanual coordination, transitions from antiphase to inphase coordination (a pitchfork bifurcation); monostability after the transition and hysteresis. Later on, to accommodate a variety of new experimental observations on sensorimotor coordination, Kelso, DelColle and Schöner [19] added the (lowest order) *symmetry breaking term*, $\delta\omega$. It is crucial to realize that this changes the entire character of the coordination dynamics and leads to a number of other dynamical effects such as fixed point shift, saddle node bifurcations, phase wrapping and the peculiarly intriguing phenomenon of 'phase trapping' (see below). In the original HKB model which assumed symmetry, pure inphase and pure antiphase are obviously idealized coordination states in a coupled system composed of identical components. Because the components of biological systems are seldom, if ever, identical, symmetry breaking turns out to be fundamental for our interpretations of coordination. Equation (2) of course, accommodates both idealized symmetry ($\delta\omega = 0$) and broken symmetry ($\delta\omega >$ and < 0).

2 Phase synchrony in the brain

The elementary coordination dynamics (Eq.2) pertain to nonlinearly coupled oscillatory processes. Oscillations are ubiquitous in the brain and are known, since the time of Hans Berger in the 30's, to occur in different frequency bands. The underlying biophysics of these oscillations is a topic of much current interest in the neurosciences. Beyond their intrinsic relevance, oscillations are also thought to hold the key to solving the so-called "binding" problem (binding, of course, is just another word for coordination). For example, cells that respond to particular features of an object are scattered all over visual cortex. The binding idea is that in order to create a complete image of an object, cell activities have to be integrated. Moreover, different attributes of an object in the field of view - form, color, motion and so forth - are thought to be analyzed by separate processing pathways. The notion is that these too have to be coordinated or 'bound' together somehow.

How do distant neurons responding to features of a single object, pool information together to create a coherent percept? The answer appears to be that neurons fire in unison. Gray, Singer and colleagues [4] found that oscillations at about 40 Hz (the gamma frequency) briefly occur in local field potentials and single neurons sometimes separated by long distances across cortical columns and even hemispheres - when light bars of the same orientation moving in the same direction are presented to anesthetized cats. For present purposes, the key point is not the oscillations per se, but rather that the oscillations are in synchrony with a relative phase of zero. That is, the relevant information for the brain seems to lie not (or not only) in the oscillations but in the phase-locked synchrony between them. More recently, the same kind of phenomenon has been seen in work by Fries et al. [2]. When a monkey attends to a visual grating there is a rapid increase in synchronization in the gamma range in V4 neurons when the stimulus is attended to, but not in V4 neurons to distractor objects. So, whether it is the hallmark of perceptual unity, conscious awareness or a decision to focus attention, rhythmic synchrony appears to be crucial. My point here is that *as far as coordination is concerned the coupling among oscillatory processes always reflects meaningful information*. What could be more relevant to a system's function than information about how its parts communicate?

We know of course that the dynamics are far richer than synchronous in-phase oscillations. For example, neurons and neuronal populations of the brain do not have to be (and more likely are not) oscillating at the same frequency. Also, they don't have to be in phase with each other. Indeed an advantage of a phase coding scheme for information processing in the brain is that the phase relation can take on any value between 0 and 2π rad. Also, since our early studies of phase transitions there is now plenty of evidence that abrupt transitions from one phase relation to another can occur in both brain and behavior. So how does this richer dynamics come about? What factors produce it?

3 Visualizing the coordination law

Let's remember that our basic archetype of coordination dynamics (Eq.2) possesses a fundamental broken symmetry, that is, the intrinsic properties of the parts being coordinated are not identical. Specifically, they possess different natural frequencies. Let's also recognize that nothing happens in biology unless there is interaction or coupling, from the molecular level on up. From these two factors and their interplay coordination emerges in a self-organized fashion. This is shown in Figure 1, which plots the coordination variable phi and its derivative phi dot as a function of increasing differences between the components ($\delta\omega$).

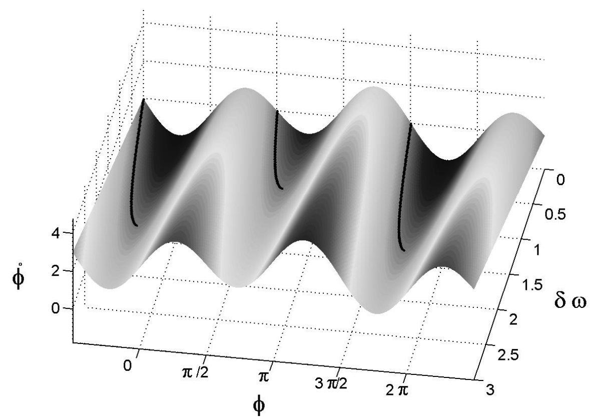

FIG. 1. Adaptive change, bistability and bifurcation in the elementary coordination dynamics (Eq.2). Parameters: a=0.5, b=0.7.

Looking at the top of the figure, we see - for a fixed value of the coupling strength - that there are two stable fixed points (black dots), one near $\phi = 0$ and one near $\phi = \pi$. The coordination dynamics are thus *bistable*, a minimally necessary condition for multifunctionality in biological systems. Notice that this coupling strength is sufficient to keep the components together even though the frequency differences between the components increases. (A relevant fact due to Kryukov [22] is that neuromodulatory influences are capable of altering the natural firing frequencies of neural oscillators). Notice also that the fixed points shift away from perfect in-phase and anti-phase in order to accommodate differences between the components: the coordination dynamics may be said to be *adaptive.*

Turning our attention to the right side of the figure we see that the stable and unstable fixed points surrounding antiphase coordination collide, leaving the system with only one stable coordination state near in-phase. The collision of stable and unstable fixed points is called a saddle node bifurcation. Through the generic mechanism of dynamic instability a phase transition from bistability to monostability occurs.

Following now the left side of the figure one observes once again the merging of stable and unstable fixed points of the coordination dynamics. The coupling strength is insufficient to sustain coordination near in-phase and there are no longer any fixed point phase-locked states, stable or unstable. Above the place where the fixed points merge, collide and annihilate each other, has coordination ceased to exist? Notice that despite the absence of attractors (and their repelling partners) the surface representing our coordination law still retains its curvature. Even though there are no fixed points of the coordination dynamics there is still a beautifully articulated surface. What does this mean?

What it means is that although attractors and repellers no longer exist, *there is still attraction and repulsion* in the vicinity of where the attractors and repellers used to be. What is the cause of this odd state of affairs? Before it happened, the parts, despite their intrinsic differences, were still coupled strongly enough so as to produce fully coordinated (phase- and frequency-locked) states. Now, however, although the coupling is still present, it is not sufficient to hold the parts together. The parts exhibit tendencies to do their own thing *at the same time* as they exhibit tendencies to coordinate together.

Watching the coordination variable phi evolve in time (Figure 2) we see it drift all over the phase space, as if the parts were not together. But we also see that it gets locally trapped 'in its past', near remnants or ghosts of the coordinated states around inphase and antiphase. Coordination tends to hang around longer near the formerly more stable in-phase coordination state than it does near anti-phase. And notice how the latter switches to inphase and hangs around there for a while before moving on. The parts are not quite independent, and the whole is not quite absolutely coordinated.

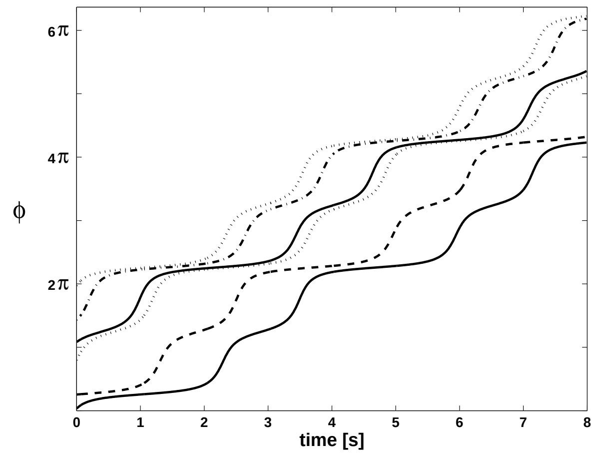

FIG. 2. The phase evolution of the coordination dynamics after the fixed points have disappeared. Parameters: a=0.5, b=1.6, $\delta\omega$=3.8.

Let's summarize all this with a few principles [15]. The basic 'two-ness' or bistability of the coordination dynamics is of course an essentially nonlinear phenomenon. I call this the *CEVA Principle* where CEVA stands for the Coexistence of Equally Valid Alternatives. In our simple archetype, the equally valid alternatives are in-phase and antiphase. Which one is chosen - given a choice - is based on stability criteria. If you ask people in a large audience to wiggle their fingers back and forth they will invariably choose the more stable in-phase pattern. A further intrinsic aspect of the coordination dynamics is the Coexistence of Opponent Tendencies or COT; stability and instability coexist as the stable and unstable fixed points of the coordination dynamics. Transitions, of course, constitute *selection* in coordination dynamics. One state is selected out of (here) two (and in general, many). A kind of decision-making occurs due, in this case to dynamic instability. I call this the *SVI* principle: Selection Via Instability. And last, but by no means least, the coordination dynamics contains a metastable regime in which there is attraction without attractors. This is literally the *PIB* principle, the Principle of the In-Between.

4 Back to the brain

In the so-called metastable regime of the coordination dynamics, the tendency of the parts to express their own autonomy and the tendency for the parts to work together coexist all at once. This speaks to a longstanding debate in brain theory about whether the brain is functionally integrated as a whole or functionally segregated into specialized neural regions (modules) that are highly localized and independent. The Principle of the In-Between says it is both ... at the same time. Tendencies for phase synchrony coexist with tendencies for the parts to remain autonomous.

Elsewhere [14] I have proposed that metastable coordination dynamics - in which there is a simultaneously ongoing interplay between phase synchrony (due to coupling) and phase scattering (due to independence among the parts) - may be the main way the brain works (see also [3]). A number of recent studies bear this picture out ([32] for review). Statistical measures of complexity also support the balanced interplay between integrating and segregating influences [31]. In the metastable regime, informationally relevant dynamic links among neural populations can be transiently formed and dispersed as the stream of perception, action and memory flows.

5 The creation of information

There is another reason for proposing metastable coordination dynamics as the essential way the brain works. It concerns an analogy to the way physicists understand how we know the universe we live in. According to Quantum Mechanics, out of a universe in which quantum indeterminacy rules - the wave function is spread out over all of space - nature selects an alternative. Information is thereby created. The way this is done in practice is that a device is built in which an interactive material is placed in a physically, electrically or chemically metastable state. According to the late quantum measurement theorist, H.S. Greene (who worked with Dirac and other founders of QM):

"It is the observable transition between this metastable state and a more stable state that conveys the essential information concerning a submicroscopic event that would otherwise go undetected... The functional material of the detector must be macroscopic and in a metastable state which allows the quantal interaction to become manifest at the macroscopic level" [5], p.173).

This is how some physicists view the creation of information: bit from it, as it were (in contrast to John Archibald Wheeler's 'it from bit'). Quantum Mechanics thus implies the creation of new information in the process of measurement and observation. Likewise, we have seen in the human brain that information (as a marginally coupled, phase-locked state) is created and destroyed in the metastable regime of the coordination dynamics, where tendencies for apartness and togetherness, individual and collective, segregation and integration, phase synchrony and phase scattering coexist. New information is created because the system operates in a special régime where the slightest nudge will put it into a new coordinated state. In this way, the (essentially nonlinear) coordination dynamics creates new, informationally meaningful coordination states that can be stabilized over time. The *stability of information over time* is guaranteed by the coupling between component parts and processes and constitutes a dynamic kind of (nonhereditary) memory.

It is not a big step, then, to say that once created, this information can then guide, modify and direct the system's dynamics. That too has been amply demonstrated in studies of intentional change, environmental change, learning and so forth. A number of years ago, for example, it was demonstrated both empirically and theoretically that an intentional goal - as memorized information - acts in the same informational space as the coordination dynamics [18], [27], see also [24].

6 Agency and directedness

Self-organizing processes, in the manner of Haken's synergetics, provide a theoretical foundation for all forms of coordination. However, we do not want to throw the baby out with the bathwater. Coordinated behavior often has a goal-directedness to it as well. We humans, for example, have no doubt whatsoever that it is us, and us alone, that direct the motions of our own bodies. Where do agency and directedness come from? Our discussion above suggests that spontaneous self-organizing coordination tendencies give rise to agency; that the most fundamental kind of consciousness, the awareness of self, springs from the ground of spontaneous self-organized activity.

Think, for example, what happens when human embryos develop - 'Im Anfang war die Tat', as Goethe said - in the beginning was the act. In the embryo, motorneurons appear well before their sensory counterparts as Viktor Hamburger and others have shown many years ago. The elementary spontaneous movements we are born with consist of a large repertoire of spontaneous (thus self-organized) movements - making a fist, kicking, sucking, etc. etc. Only at some point does the child realize - through his own movements and the sensations they give rise to - that these movements are his own. If one attaches a string to his foot, he comes to realize that it is *his* kicking movements that are causing the mobile to move in ways that *he* likes.

The pre-existing repertoire enables activities to happen before we make them happen. *Spontaneous (self-organized) coordination tendencies thus lie at the origins of conscious agency.* They are, in the words of the philosopher Maxine Sheets-Johnstone, "the mother of all cognition", presaging every conscious mind that ever said "I". From spontaneous self-organized behavior emerges the self - "I am" "I do" and from there a huge range of potentialities ('I can do'). "I-ness" arises from spontaneity, and it is this "I" that directs human action. As Sheets-Johnstone [26] cogently remarks, we literally discover ourselves in movement. In our spontaneity of movement, we discover arms that extend, mouths that open, knees that flex and so forth. We make sense of ourselves as living things.

It does not seem too far of a stretch of the imagination to propose that evolutionarily constrained processes of self-organization - real organisms coupled to real environments living in the metastable regime of their coordination dynamics - are at the origins of information and agency itself. This step may signal an end to false contrasts about whether coordination in living things is a directed or self-organized process and point rather to their inherently complementary and unified nature.

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