Walls and Borders and Strangers on the Shore: On Learning to Live Together from the Perspective of the Science of Coordination and the Complementary Nature

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> *Man tries to make for himself in the fashion that suits him best a simplified and intelligible picture of the world; he then tries to some extent to substitute this cosmos of his for the world of experience, and thus to overcome it. This is what the painter, the poet, the speculative philosopher, and the natural scientist do, each in his own fashion. Each makes this cosmos and its construction the pivot of his emotional life, in order to find in this way the peace and security which he cannot find in the narrow whirlpool of personal experience.*
>
> A. Einstein

Overview. To learn to live together requires a world mind-shift. In this paper I will attempt to articulate what this mind-shift involves and how it is constituted. As remarked by previous Olympians of the Mind (the solution to learning to live together rests ultimately not on science or technology or economics or politics, but on human decency and compassion. Humanity must realize that our collective fates are intertwined both in terms of uniqueness and interdependence. Regardless of sex, race, religion, economic opportunities, individual passions or ambitions, we must somehow weave a "we" to see native and stranger on the same footing. We will not learn to live together until we face this collective reality. The science of coordination (Coordination Dynamics) and the philosophy that arises from and underlies this science (The Complementary Nature) offer a way to change the world to one we all need, one where together we can live in a truly relational way that is without prejudice and goes beyond simple tolerance of the other. Some of the key empirically-based concepts I will discuss are *synergy*—the "working together" aspect as a self-organized entity (in the sense of the physics of open, nonequilibrium systems) and as the significant unit of biological

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J. A. S. Kelso (ed.), *Learning To Live Together: Promoting Social Harmony*,
https://doi.org/10.1007/978-3-319-90659-1_10

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coordination (in the sense of synergistic selection); *learning*—the modification of pre-existing biases and dispositions; the *nature of change*—a process unpredictably sudden and abrupt or slow and tortuous depending on identifiable competitive or cooperative mechanisms; *agency*—a fundamentally relational and dynamic attribute not isolated in the individual mind; and finally, the *metastable dynamics* of the human brain—how the tendencies for the parts of the brain to integrate co-exist with tendencies for individual autonomy and segregation. I will present new experimental evidence which demonstrates that a critical level of diversity separates these two idealized régimes. Whereas bistability is the basis for polarized either/or thinking and phase transitions, which allow one to switch from one polar extreme to the other, the in-between metastable régime—which contains neither stable nor unstable states (no states at all in fact)—gives rise to a far more fluid, complementary mode of operation (hence, The Complementary Nature) in which it is possible for apparent contrarieties (e.g., integration ∼ segregation, unity ∼ diversity, individual ∼ collective, self ∼ other, cooperation ∼ competition, chance ∼ choice, boundary ∼ domain, etc., etc.) to coexist in the mind at the same time. The political, ethical and educational consequences of the metastable brain ∼ mind that sees contrarieties as complementary are many, including a fundamentally "new" triadic logic not of the excluded (after Aristotle) but of the *included* middle, signified by the tilde or squiggle (∼) symbol. The metastable brain ∼ mind, if we can tap into it, signals the end of dualism, the grand "either/or," and "the perpetual contradiction of opposites" that is at the very core of religious and ideological conflict throughout history.

Preamble. As I sit down to write my thoughts on "Learning to Live Together", Hurricane Irma is heading toward the South of Florida, where I live, at 185 miles per/h. People are afraid, and rightly so, but also in part because a major tragedy occurred in Texas recently when Hurricane Harvey struck. Prior context matters. Fear brings out the worst in people. When resources are scarce and time is short, people tend to behave badly. One only has to watch them when they are queuing up to fill their cars with petrol or 'gas' (in American English). Their movements and gestures are jittery and the language is coarse. The slightest change can trigger a strong reaction. Ordinary discourse goes out the window, replaced by a snarl here and a 'fuck you' there. If you don't have a fueled means of transport to escape the storm, you and your kin are trapped, man. Gas is running out and competition is fierce. There's a reason why the old Darwinian slogan of "survival of the fittest" has lasted over the years. It's me against you and it's ugly.

Yet, you only have to observe people's behavior after the storm in Texas to see plenty of evidence for their good side. The giving, the sharing, the brave, sometimes heroic deeds to save others in distress—it warms the heart to see it. High levels of empathy in the TV viewing audience are invoked followed by material, philanthropic giving. Strange things us humans. Fiercely competitive on the one hand, cooperative and altruistic on the other. How are we to understand the nature of man?

These passing thoughts are not unrelated to our topic of learning to live together. The availability of resources does matter. Our evolutionary origins and history do matter. How we were brought up does matter. Environment and education do matter. Inequality is an issue. Etcetera, etcetera, etcetera as the King of Siam used to say. But I don't think any of these factors are the true heart of the problem. In my view, to learn to live together requires a world mindshift. My aim in this paper is a small attempt to articulate what the mindshift might involve, how it is constituted. Importantly, it's not only about the mindshift itself, but how it fits into a world that is heavily polarized on many levels. I should say also that the world I am talking about is most likely limited to those in so-called democracies who at least think they can do something about it—though in actuality their voice is often muted and smothered. In every country, in every continent, the majority of people cannot do a damned thing. In my view they will stay silent until they think and act in a certain way and have the will to do something about it.

The sculpture shown in Fig. 1 is called "Hands across the Divide" and stands at the end of the Craigavon bridge in Derry, in the northern part of Ireland—the place where I am from–and of course is symbolic of the hope for an end to conflict and division. In this, the sculpture resonates with the 8th and 9th Olympiads of the Mind (and indeed earlier Olympiads—all organized by an extraordinary human being, Dr. Epimenides Haidemenakis) which aim to cultivate greater understanding, tolerance and unity among human beings worldwide.

What can science and in particular brain and behavioral research do to end conflict and promote global harmony—to help us learn to live together? On an earlier occasion[1] my position was that despite all the successes of contemporary neuroscience in alleviating the many neuropsychiatric and neurological diseases that afflict us—even removing the stigma of mental illness and epilepsy—not much has really changed. Looking around the world today it is difficult to avoid the conclusion that we human beings are the way we are. Wars, poverty, violence, fear, greed, etc. permeate modern life just as they have for centuries. All our knowledge of the brain, I said then, and all the marvelous technological developments that have helped produce this knowledge, have not led to much wisdom or deeper understanding of ourselves. To turn scientific knowledge into wisdom, I argued, seems to involve an alchemy that has escaped us….

However, I believe there is light at the end of the tunnel. There are at least five reasons for hope that I will discuss. One is that the 'new science of coordination' called *coordination dynamics* promotes the centrality of *synergy* as the fundamental unit of life. Synergy is from the Greek *sunergia* and means "working together". The significance of synergy is that it places emphasis on the effectiveness of cooperative interaction between two or more agents—related or not—and is the key to our survival and to learning to live together. Two is that the basis for how synergies arise, persist and change in natural systems (including us humans) is known to rest

[1]Kelso (2010) Coordination and The Complementary Nature. Nour Foundation, New York. https://www.youtube.com/watch?v=FHd5FLwTspk.

Fig. 1 ***Reconciliation/Hands across the Divide*** *by the Sculptor, Maurice Harron who like the author was born and grew up in Derry, Northern Ireland. The sculpture is situated in Carlisle Square in Derry ~ Londonderry overlooking the Craigavon Bridge which spans the River Foyle. As a result of 'the troubles', the bridge came to largely separate Protestant and Catholic communities. Bridges have a dual function: they can unite or divide*

on the joint action of two fundamental forces of nature: evolution and self-organization. Three is that synergies may be expressed in a common theoretical language, that of informationally meaningful, (predominantly) bidirectionally coupled, nonlinear dynamical systems (Coordination Dynamics). Four is that the empirical and mathematical study of the latter over the last 30 years in laboratories and research centers around the world have revealed a feature called *metastability* that, among other attributes, has been hailed as a *new principle of brain function*. Fifth, is that this new principle leads directly to a mindset that signals the end of polarization, here considered to be the root cause of strife and conflict. I will touch on all these aspects in what follows.

Coordination Dynamics: The new science of coordination. Many moons ago, my colleagues, students and I set out to understand (if not solve) the problem of coordination in living things. Our work was inspired by the eminent theoretical biologist Howard Pattee (1976) who referred to the problem of coordination as crucial to understanding the physical basis of life. We chose movement, the animated, living movement of human beings as the test field, in part because of a childhood love for sports and the performing arts, and in part because like gravity, most people take their innate capacity to move for granted. Like most scientists at the time, and even more nowadays, we proceeded in classical reductionist fashion.

A first step was to identify *the significant units of biological coordination* and their key properties. This is not a trivial problem nor can it be assumed a priori: animate movement is not made up merely of a list of component parts such as molecules, muscles, neurons and brains, but rather has to do with how these many parts *relate* to each other. Let me dispel any confusion between units *in* and units *of*. The former analyzes units as if they were a piece in a puzzle or an ingredient in a cake. A pendulum, for example, consists of a number of components that can be thought of as the units *in* a pendulum system. But it is *the relations among the components* that define the *function* of the pendulum system. With some notable exceptions (e.g. Noble 2008) biology classifies its units—genes, enzymes, proteins, cells, etc. in terms of their anatomy. The units we were after are units of function[2] which go beyond the particular 'parts list' of components of which they are constituted.

What we found is that the significant units of coordination (and, we think, of life itself) are *functional* synergies or *coordinative structures*—ensembles of interacting neurons, muscles and joints temporarily assembled to accomplish a task or fulfill a function. "Synergies of meaningful movement" (to use the philosopher-biologist Maxine Sheets-Johnstone's coinage) have been hypothesized as important for motor control for over 100 years but until our research in the late 70's and early 80's the evidence was anecdotal or restricted to so-called 'pre-wired' rhythmical activities such as locomotion and respiration. Much work has been done since, of course, and books written (e.g. Kelso 1995; Latash 2008; Sheets-Johnstone 1999/2011). So why are synergies preferred over other candidates such as currently popular circuits and networks? Only synergies embrace variability in structure and function (see also Stergiou, this volume). Only synergies handle the fact that many different components can produce the same function (biological degeneracy) and that the same components may be assembled to produce multiple functions (pluripotentiality). Synergies or coordinative structures are not restricted to muscles; they have been identified at many scales from the cellular and neural, to the cognitive and social (e.g. Oullier et al. 2008).

The deeper reasons for synergies as the basic units of biological organization are, as mentioned above, that they are the result of two elemental forces, evolution and self-organization. When cooperation occurs between two or more entities and that cooperation proves to be functionally advantageous, *synergistic selection* is deemed to occur. According to the latter, cooperating groups may gain an advantage in terms of survival and reproduction compared to groups of non-cooperating individuals. This effect is under appreciated though it occurs at all levels of biological organization (see Maynard-Smith and Szathmary 1995; Corning 2010). The other force, unknown to Darwin and mostly ignored by evolutionary biology is *self-organization*—the discovery of emergent cooperative phenomena in natural systems. Of significance here is that the most fundamental form of self-organization in systems that are open to exchanges of energy and matter—as the physicist Hermann Haken has shown comprehensively in his pioneering research on lasers—are nonequilibrium phase transitions (Haken 1977/1983). And of even more significance for us is that all the predicted features of nonequilibrium phase transitions including enhancement of fluctuations and critical slowing down have been demonstrated in coordinated movement and the human brain (Kelso et al. 2013 for review). For matters of movement and mind, self-organizing principles are

[2]Notwithstanding the fact that what we call structures, like bones and such, are really slow, relatively long lasting functions. The level and timescale of analysis constrain the terminology. Here, no dichotomy is brokered between structure and function.

expressed in terms of informationally coupled dynamical systems *aka* Coordination Dynamics, Kelso 2009).

A key concept of self-organizing coordination dynamics is the so-called *order parameter* or *collective variable*, a term that expresses cooperative behavior in open, nonequilibrium systems with many degrees of freedom (Haken 1983). It turns out that order parameters (OPs) are important for understanding *any* kind of coordination, from the brain to players in teams, from ballet dancers to championship rowers, because they constitute the *content* of the underlying dynamics (Fuchs and Kelso 2017). Not only are OPs expressions of emergent patterns among interacting components and processes, they in turn modify the very components whose interactions create them. This confluence of top-down and bottom up processes results in *circular or reciprocal causality*, an essential concept in Coordination Dynamics (see Fig. 2).

Unlike the laws of motion of physical bodies, *laws of coordination are expressed as the flow of coordination states produced by functional synergies or coordinative structures.* The latter span many different kinds of things and participate in many processes and events at many scales. In their most elementary form, coordination laws are governed by *symmetry* (and symmetry breaking) and arise from *nonlinear coupling* among the very components, processes and events that constitute the coordinative structure on a given level of description. An example is the well-known extended HKB equation of coordinated movement:

$$\dot{\phi} = \delta\omega - a\sin\phi - 2b\sin 2\phi + \sqrt{Q}\xi_t \tag{1}$$

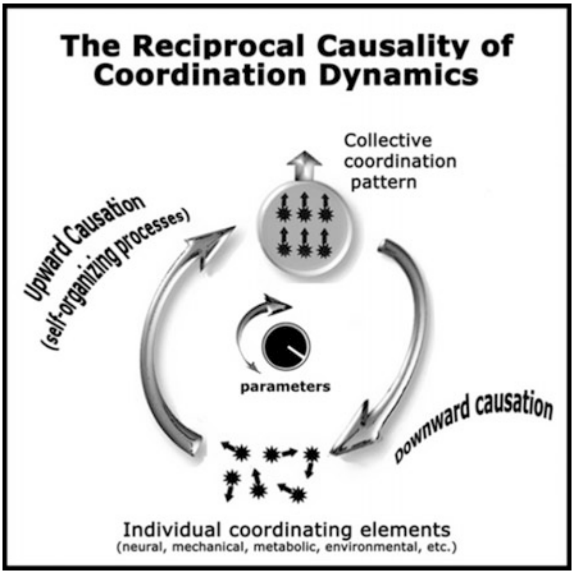

Fig. 2 ***The circular or reciprocal causality of self-organizing coordination dynamics***. *Collective coordination patterns characteristic of a functional synergy or coordinative structure on a given level of description arise from the interaction among variable subsystems and processes (upward causation) yet reciprocally constrain the behavior of these coordinating elements (downward causation)*

where ϕ is the Order Parameter, in this case the relative phase between two interacting components, the dot above ϕ standing for the derivative with respect to time, a and b are coupling parameters, $\sqrt{Q}\xi_t$ is a (delta-correlated) noise term of strength Q, and $\delta\omega$ is a symmetry breaking term expressing the fact that each coordinating element possesses its own intrinsic behavior. Akin to the Schrödinger equation which describes how the quantum state of a system evolves over time, Eq. (1) specifies how the coordination states of a system evolve over time. Figure 3 shows the layout of attractors of this elementary coordination law.

When $\dot{\phi}$ reaches zero (flow line becoming white), the system ceases to change and fixed point behavior is observed. Note that the fixed points here refer to *emergent coordinative states* produced by the nonlinearly coupled elements that constitute the synergy or coordinative structure. Stable and unstable fixed points at the intersection of the flow lines with the isoplane $\dot{\phi}$=0 are represented as filled and open circles respectively. To illustrate the different régimes of the system, three representative lines labeled 1 to 3 fix $\delta\omega$ at increasing values. Following the flow line 1 from left to right, two stable fixed points (filled circles) and two unstable fixed points (open circles) exist. This flow belongs to the multistable (here *bistable*) régime. Following line 2 from left to right, one pair of stable and unstable fixed points is met on the left, but notice the complete disappearance of fixed point behavior on the right side of the figure. That is, a qualitative change (*bifurcation; phase transition*) has occurred due to the loss of stability of the coordination state near antiphase, π rad. The flow now belongs to the monostable régime. Following

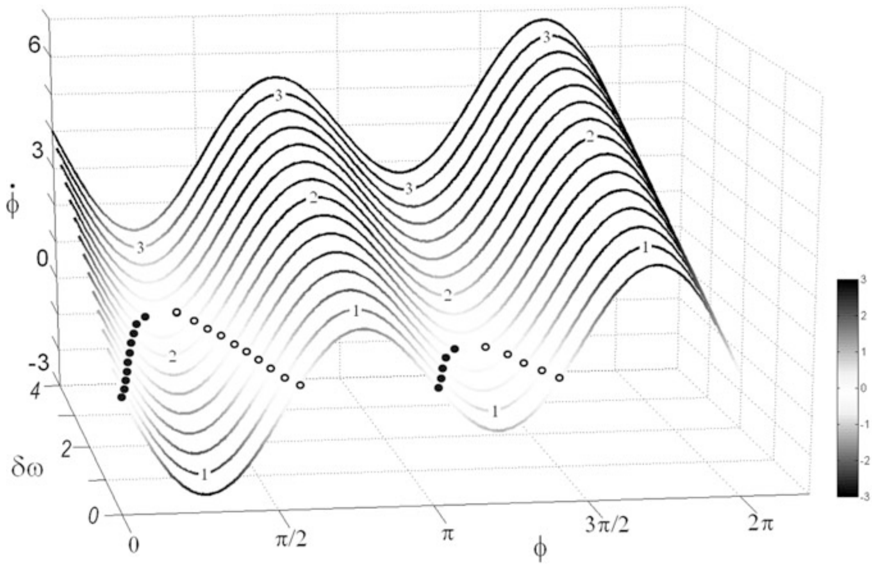

Fig. 3 ***Elementary coordination law*** (Eq. 1). *Surface formed by a family of flows of the Order Parameter or coordination variable* ϕ *(in radians) as a function of* $\dot{\phi}$ *for increasing values of* $\delta\omega$ *between 0 and 4. For this example, the coupling is fixed:* $a = 1$ *and* $b = 1$ (see text for details)

line 3 from left to right, no stable or unstable fixed points exist yet coordination has not completely disappeared. This flow corresponds to the *metastable* régime, a subtle blend of coupling and intrinsic differences between the parts in which behavior is neither completely ordered (synchronized) nor completely disordered (desynchronized). *It is the subtle interplay between the coupling (b/a) and the symmetry breaking term* $\delta\omega$ *in* Eq. 1 *that gives rise to metastability*.

Equation 1 is somewhat odd. Even though it is an order parameter equation of motion that is designed to describe the evolution of *collective behavior* (in words, phi dot is a function of phi), it includes also a parameter $\delta\omega$ that arises as a result of differences (*heterogeneity*) among the *individual components*. Equation 1 is thus a strange mixture of the whole and the parts, the global and the local, the cooperative and the competitive, the collective and the individual. Were the components identical, i.e., no diversity, $\delta\omega$ would be zero and we would not see component differences affecting the behavior of the whole. Equation 1 would simply reflect the behavior of the collective untarnished by component properties, a purely emergent interaction—the HKB equation. It is the fact that *both* the components *and* their (nonlinear) interaction appear at the same level of description that gives rise to the array of coexisting tendencies characteristic of metastability. Equation 1 is a basic representation of a *synergy* or *coordinative structure*: a low dimensional dynamic of a multi- and metastable organization in which the tendency of the parts to act together coexists with a tendency of the parts to do their own thing (Kelso 1995, Ch 4; for more on synergies, see Kelso 2009a, b). It is metastability that endows the synergy with robustness and flexibility, enabling the same parts to participate in multiple functions. If the synergy is a unit of life, then it is metastable dynamics that brings it alive. We'll come back to this point and its broader implications in the final section of the paper.

On Learning and the Nature of Change. So far, Coordination Dynamics (CD) provides an empirically validated theoretical account of what "working together" means and places the functional synergy on the pedestal of biological coordination. What does the CD say about *learning*? Only a few brief remarks can be made here (but see Kostrubiec et al. 2012 for a review of empirical and theoretical modeling work on learning conducted with Pier-Giorgio Zanone and colleagues in Toulouse over a period of 25 years). Coordination Dynamics defines *learning as the modification of a pre-existing repertoire that is unique to each individual*. Thus, in CD the *individual is the significant unit of analysis*; every individual enters the learning situation with their own biases/predispositions/coordination tendencies. This individual signature (which must be quantified) is referred to as *intrinsic dynamics*. Here again, the dynamics refer to the dynamics of collective variables that span both the organism and the environment. What changes during learning? Experiments show that not just the pattern to be learned changes during learning, *but the entire landscape of the intrinsic dynamics/pre-existing repertoire*. What is the nature of change? In his *Autobiography*, Charles Darwin, based on observations of his own children, concluded that changes due to learning "have all had a gradual and natural origin". Our results show that *learning can be smooth and continuous or abrupt and qualitative depending on the relationship* *between the learner's pre-existing repertoire and the new information that is to be learned. Competition* between the pre-existing repertoire and new information is a key mechanism that dictates the nature of change. Stability, not just error correction is the overall criterion for learning. Indeed, the brain areas recruited for learning and their level of activation are directly related to the stability of performance (Jantzen et al. 2009; DeLuca et al. 2010). Bottom line?

According to Coordination Dynamics, if you want to change anything and have it persist "permanently" (as opposed to being a mere transient)—in other words *learn*—you'd better know the system's intrinsic dynamics. Knowing the latter means you know *what* to modify, and whether to use competitive or cooperative mechanisms to cause abrupt or gradual change (see Fig. 4). I suspect this principle of learning operates at all levels, from individuals through society and is at the heart of significant political change. Foreign policy, diplomacy and acts of aggression often flounder because of ignorance about the intrinsic dynamics of the system that they aim to influence or change. Obtaining measures of intrinsic dynamics in all these situations constitutes a major challenge—though with major payoffs because it means you know what to change. Economically speaking, as the pharmaceutical business has begun to appreciate, knowing the intrinsic dynamics of the individual is at the core of so-called personalized medicine—for example in understanding why a drug has a positive effect on one person and no effect on another. Statistical studies in clinical populations hide this fact.

On Agency. *Learning to live together requires purpose and intent*. There must be a desire to make things happen. Though grounded in evolutionary and self-organizing processes, synergies or coordinative structures are meaningful and goal-directed. Working and living together is not simply the result of a reflexive herd or group instinct: it requires agency. Agency means action toward an end. So where do agency and goal-directedness come from? A main aspect of self-organizing dynamical systems is that the emergence of pattern and pattern switching occur *spontaneously,* solely as a result of the dynamics of the system: no specific ordering influence from the outside and no homunculus-like agent or program inside is responsible for the behavior observed. Yet somehow, that is, without magic or some vital force, what we call agency must spring from the ground of spontaneous self-organized activity (Kelso 2002). A clue comes from studies of 3 month-old human babies (Rovee and Rovee 1969). When babies are comfortable and lying in their crib they kick their legs and move their arms spontaneously. After a while they become fussy and so to amuse them mothers will sometimes attach a mobile above their head that looks attractive and makes noises that babies seem to like. But this doesn't last forever. Maybe the baby gets bored or attention toward the mobile saturates. What if you tie a ribbon to the baby's ankles and attach it to the mobile hanging over the baby's crib? By virtue of the coupling, any spontaneous foot or leg movements will cause the mobile to move. Now look what happens next. Suddenly the baby increases his/her kicking rate by a factor of 4! The baby realizes that it, not some outside force, is making the mobile move! The idea is that when the baby perceives it is causing the world to change it experiences itself as an agent for the very first time.

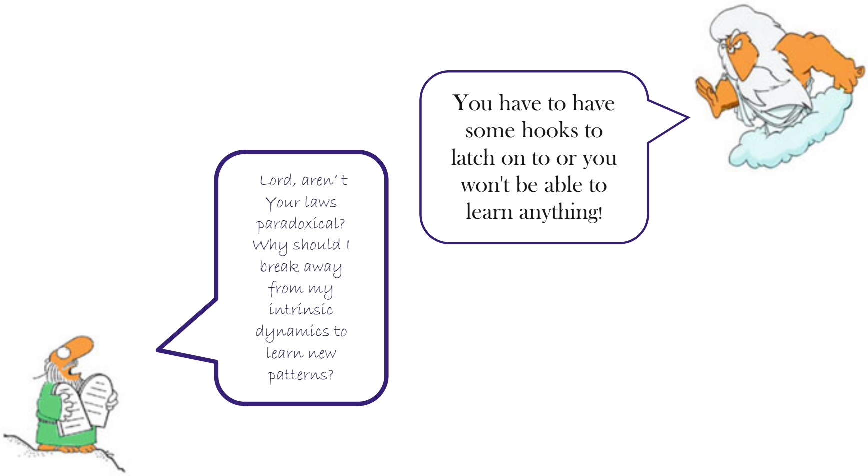

Fig. 4 ***One of the messages from research on the coordination dynamics of learning*** (thanks to Vivianne Kostrubiec for cartoon)

It seems that the key to the emergence of conscious agency is not only spontaneous movement (which is a fundamental component, nevertheless) but the bidirectional coupling (by means of the tether) between the baby and the world. Theoretically speaking, a coordinative structure *qua* coupled dynamical system is formed when the (notably prelinguistic) infant discovers itself as an agent ('this is me'), that is, when the baby realizes it can *make things happen*. In this theory (Kelso 2016; Kelso and Fuchs 2016) the birth of agency and its causative powers ("I do", "I can do") corresponds to a *phase transition* of a coordination dynamics whose key variables span the interaction between the organism (baby) and its environment (the moving mobile). This igniting of agency has a eureka-like, 'aha' effect; mathematically, it corresponds to a bifurcation in the coupled dynamics. Here, coupled dynamics refers to the coordinated *relation* between the baby's movements and the (kinesthetic, visual, auditory and emotional) consequences they produce. Bifurcations are the mathematical equivalent of phase transitions, qualitative changes in coordinative states. The main mechanism underlying the origin of self as a causal agent involves *positive feedback*: when the baby's initially spontaneous movements cause the world to change, their perceived consequences have a sudden and sustained amplifying effect on the baby's further actions. This autocatalytic mechanism is continuous with our understanding of how biological form develops and of the feedforward network motifs so ubiquitous in the design of biological circuits (Alon 2007). The deep irony of this theory of the coordination dynamics of moving bodies is that the most primitive form of self-organization known in biological coordination (brains included), a synergetic phase transition, gives rise to self. The root soil of agency, as Sheets-Johnstone (Sheets-Johnstone 1999/2011) would say, rests on primal animation, on being alive and moving.

Metastable Mind—The key to learning to learning to live together? What are the implications of multi- and metastable coordination dynamics (cf. Fig. 3) for understanding the mind? Like nature and nurture, the contents of the mind and the dynamics of the mind are inextricably connected. Thoughts are not static: Like the flow of a river, they emerge and disappear as patterns in a constantly shifting dynamic system (Kelso 1995). Though this is a nice metaphor, science demands we go beyond it to seek description and explanation. In particular, we would like to explain or understand the brain ~ mind relation—if possible–with a single theoretical model. Figure 5 is intended to convey the gist of the story. On the left side of the middle panel, two areas of the brain (for the sake of simplicity) are shown to be active. This acknowledges a simple fact—or at least a dominant assumption in contemporary neuroscience: The contents of thoughts depend on the neural structures activated. However, identifying thought-specific structures and circuitry using brain mapping, important though it may be, is hardly sufficient to tell us how *thinking* works. Active, dynamic processes like perceiving, attending, remembering and deciding that are associated with the word "thinking" are not restricted to particular brain locations, but rather emerge as patterns of interaction in time among widely distributed neural ensembles, and in general between human beings and their worlds.

One of the great riddles of contemporary neuroscience is how the multiple, diverse and specialized areas of the brain are coordinated to give rise to thinking and coherent goal-directed behavior. A key fact embraced by Coordination Dynamics is that neuronal assemblies in different parts of the brain oscillate at different frequencies. Such oscillatory activity is a prime example of self-organization in the brain. But oscillation, though necessary is not sufficient. It is, rather, that oscillations are coupled or "bound" together into a coherent network when people attend to a stimulus, perceive, remember, decide and act (e.g., Başar 2004; Bressler and Kelso 2001; Buzsáki 2006; Kelso 1995; Varela, et al. 2001; Singer 2005, for reviews). This is a dynamic, self-assembling process, parts of the brain engaging and disengaging in time, as in a proverbial country square dance. In the simplest case shown in the left column of Fig. 5, oscillations in different brain regions can lock "in-phase", brain activities rising and falling together, or "anti-phase", one oscillatory brain activity reaching its peak as another hits its trough and vice versa. In-phase and antiphase are just two out of many possible multistable, phase attractive states that can exist between multiple, different, specialized brain areas depending on their respective intrinsic properties and functional connectivity. More broadly, the organism and its environment are embedded in a nested frame of rhythms ranging from rest ~ activity and sleep cycles to circadian and seasonal rhythms that both modify and are modified by behavior, development and aging.

The top left part of Fig. 5 conveys the essential *bistable* nature of brain ~ mind. Two states are possible for identical parameter values: which state one enters depends on initial and boundary conditions. According to Coordination Dynamics, *bistability is the basis of polarization and the either/or*. Note that this does not necessarily imply any judgment of good or bad. Polarization, for example, may be

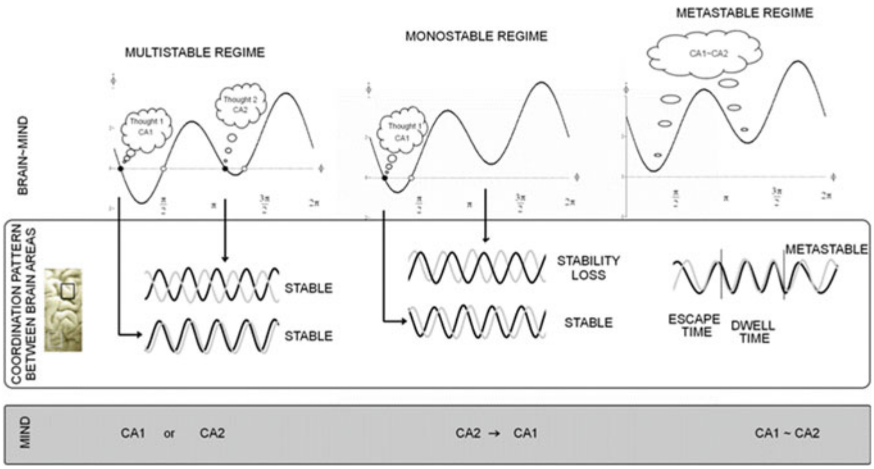

Fig. 5 ***Elementary Coordination Dynamics of Brain ~ Mind.*** Middle panel represents synaptically coupled brain oscillations from two brain areas (for the sake of simplicity) whose activation is meaningful and specific to the content of "thoughts". Here "thought" is used in a generic sense; the states could refer to patterns of perceiving, emoting, remembering, deciding, acting, etc. Top left panel shows the layout of the fixed points of the relative phase dynamics (Eq. 1) in the multi- (here bi-)stable regime. Solid circles are stable and attracting; open circles are unstable and repelling (see also Fig. 3). Two states are stable corresponding to particular phase relations between groups of neurons/brain areas, representing two stable "thought" patterns (ca1 and ca2) for exactly the same parameter values. Top middle panel shows that the formerly stable pattern near antiphase switches to near inphase as a result of changing circumstances. Any ambiguity due to bistability has been removed, a "decision" or "selection" has been made and as a result, the system is monostable and confined to a single thought pattern. The switching mechanism is dynamic instability induced by changing control parameters (e.g., the coupling between the neural populations which may be altered by neuromodulators). Fluctuations (not explicitly represented here) also play a key role in spontaneous switching. Top right panel shows that all states, both stable and unstable have disappeared. This is the metastable régime. Now "thoughts" no longer correspond to fixed point, fully synchronized states of the coordination dynamics, but rather to coexisting tendencies or dispositions that have characteristic dwell times. The lowest panel called "Mind" illustrates the classical dual nature of either/or, binary oppositions between complementary aspects (ca1 *or* ca2), mind (and mindset) switching (ca2 to ca1 and *vice versa*) and the mind and mindset of the complementary nature, where both "thoughts" are held in the mind at the same time (ca1 ~ ca2) (adapted from Kelso 2008)

seen as the driving tension behind scientific progress in the sense of Thomas Kuhn (1962), and bistability may be exploited for solving ill-defined problems where the consideration of multiple interpretations of data is an advantage. Bistable, and in general multistable coordination dynamics confers many advantages on living things, in particular multifunctionality (see, e.g., Kelso 1991).

Coordination dynamics suggests that the persistence of a thought depends on the *stability* of the brain's relative phase dynamics. Some thoughts persist longer than others because the phase relations underlying them are more stable. In Fig. 5 (top left), the negative slope through the ordinate near in-phase ("thought 1") is greater, hence more stable, than its anti-phase counterpart ("thought 2"). This proposition is supported by experiments and specific neurally-based modeling which shows that different patterns of spatiotemporal brain activity are differentially stable.

So what causes thoughts to switch, the person to change her mind? The middle column of Fig. 5 offers a specific mechanism: dynamic instability. Considerable experimental evidence has demonstrated that switching in both brain and behavior is a self-organized process that takes the form of a nonequilibrium phase transition. Fluctuations play a key role, testing the stability of states and enabling the system to discover new states. In Coordination Dynamics, once the system settles into an attractor, a certain amount of noise or a perturbation is required to switch it to another attractor. Or, if internal or external conditions change when the system is near instability, a bifurcation or phase transition may occur, causing the system to switch from being multistable to monostable or vice versa (see Ditzinger and Haken 1989, 1990 for excellent examples of such modeling). Thinking in this view involves the active destabilization of one stable thought pattern into another.

A slightly different view emerges from the flow of the relative phase dynamics in the metastable régime (Fig. 5, right). Instead of thoughts corresponding to phase synchronized states in the brain that must be destabilized if switching is to occur, metastability consists of a more subtle dwell and escape dynamic in which a thought is never quite stable and merely expresses a joint *tendency* for neural areas to synchronize together and to oscillate independently. Fluid thinking, in this view, is when the brain's oscillations are neither completely synchronized nor desynchronized (see also area 2 in Fig. 3). In the metastable régime, successive visits to the remnants of the fixed points are intrinsic to the time course of the system, and do not require any external source of input. Switching occurs, of course, but continuously and without the need for additive noise or changes in parameters. From the perspective of Coordination Dynamics, the time the system dwells in each remnant depends on a subtle blend of the asymmetry of the rhythmic elements (longer dwelling for smaller asymmetry) and the strength of the coupling (longer dwelling for larger values of a and b in Eq. 1). Metastable coordination dynamics also rationalizes William James (1890) beautiful metaphor of the stream of consciousness as the flight of a bird whose life journey consists of 'perchings' (phase gathering, integrative tendencies) and 'flights' (phase scattering, segregative tendencies). Both tendencies appear to be crucial: the former to summon and create thoughts; the latter to release individual brain areas to participate in other acts of cognition, emotion and action.

Metastability (meta meaning beyond) is an entirely new conception of brain organization, not merely a blend of the old. Individualist tendencies for the diverse regions of the brain to express their independence coexist with coordinative tendencies to couple and cooperate as a whole. As we have seen, in the metastable brain local segregative and global integrative processes coexist as a complementary pair, not as conflicting theories. Reducing the strong hierarchical coupling between the parts of a complex system while allowing them to retain their individuality leads to a looser, more secure, more flexible form of functioning that promotes the creation of information. Too much autonomy of the component parts means no chance of them coordinating and communicating together. On the other hand, too much interdependence and the system gets stuck, global flexibility is lost. Well-known manifestations of too much synchronization in the brain, for example, are characteristic of diseases like Parkinson's disease and epilepsy.

Metastability is an expression of the full complexity of brains and people (Kelso 2001; Tognoli and Kelso 2014) and gives rise to a plethora of complementary pairs. In fact, it is chock full of them (Kelso and Engstrom 2006):

individual ~ collective
parts ~ whole
segregation ~ integration
choice ~ chance
competition ~ cooperation
symmetry ~ broken symmetry
stability ~ instability
states ~ tendencies/dispositions
and so forth.

The tilde (~) or squiggle symbol expresses a basic truth: both members of a complementary pair are required for understanding. One without the other is incomplete. Even polarization ~ reconciliation is a complementary pair.

It is a truism that we live in a world of 'isms'. Such distinctions have no doubt served a (sometimes malicious) purpose (think, e.g. of the term 'birtherism'). The problem is that we human beings—intentionally or not—have reified them. We hear a lot these days, for example, of the need to replace reductionism with emergentism—sometimes accompanied by fond hopes that this step will pave the way to a new global civilization. Often there is little or no scientific basis for promulgating a new worldview. "Isms" are an obstacle to understanding: they tend to result in one doctrine being defended over another rather than opening up new ideas.

Dynamically speaking, bistability is at the core of polarization and the either/or, the latter often posed as "isms". But as can be seen in Figs. 3 and 5, that way of thinking is just a (very) restricted régime of the coordination dynamics.

Metastability is telling us that it's not just about states and it's not just about one tendency or the other, but both tendencies at the same time. *Contraria sunt complementa* as Niels Bohr's famous coat of arms says, an attitude hearkened to also by "Einstein's conscience", the great Wolfgang Pauli:

> *To us the only acceptable point of view is one that recognizes both sides of reality—the quantitative and the qualitative, the physical and the psychical—as compatible with each other, and can embrace them simultaneously.* (Pauli 1952)

Inna Semetsky (2010), an eminent leader in education based at the Institute of Advanced Study for Humanity at the University of Newcastle in Australia, draws attention to disciplinary knowledge based on the classical logic of the excluded middle—where subject and object, self and other are separated. In seeking a transdisciplinary, in vivo knowledge system that connects subject and object, self

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and other she and others advocate a logic of the *included* middle, represented by the squiggle symbol of The Complementary Nature. Semetsky makes a strong case for non-dualistic transdisciplinary knowledge as being at the core of a new *ecoliteracy* movement based on sharing and cooperating with others and the inclusion of values. Facts alone will not do. For her, the task of transforming human structures into open ended ecological systems in harmony with the natural world represents a major challenge at all levels, most especially at the level of education. Here again, the complementary organism ~ environment pair, central to Coordination Dynamics—"the intercourse of the live creature with its surroundings", as Semetsky quotes Dewey as saying—is central also to ecoliteracy.

It seems that the message of metastable coordination dynamics is that there is a deep principle of complementarity underlying life, brain, mind and society. Metastability says that complementary aspects and their dynamics are found not just at the remote level of subatomic processes dealt with by quantum mechanics, or even at the level of molecular complementarity as in DNA, but at the level of human beings, human brains and human behavior–at the level, in other words, where the science of coordination plays out—Coordination Dynamics. Thinking narrowly in terms of contraries and the either/or is easy when life is simple. But in complex coordinated systems it seems that sharp dichotomies and contrarieties have to be replaced with far more subtle and sophisticated complementarities. One suspects this is true for all of nature, human nature (and human brains) included. Understanding ourselves and the way we think and behave in our relationship to the environment, to other species or relationships with others, individually as human beings, as groups, as societies, as nation states, would seem to depend on this realization.

Acknowledgements The author's research is currently supported by National Institute of Mental Health grant MH080838, the Davimos Family Endowment for Excellence in Science, and the Florida Atlantic University Foundation (Eminent Scholar in Science).

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