Chapter 48
On the Nature of Coordination in Nature

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Abstract Aiming to identify general principles governing collective behavior at multiple levels, we visit complex systems whose dynamic patterns traverse neural, behavioral, and social levels. Rather than approaching such systems from their distinct scientific perspectives, e.g., neuroscience, psychology, or sociology, we unite them in the study of their coordination dynamics. A study of multiple people coordinating their behavior, dubbed "the human fireflies experiment," reveals spatiotemporal metastability. Another study of real fireflies, often taken as the poster child for strong synchronization, also reveals a telltale spatiotemporal mixture of integration and segregation, as had an earlier investigation into the coordination of neural ensembles. Empirical data is contextualized with a theoretical model of coordination dynamics and confirms its prediction that weak coupling and broken symmetry play key roles. We conclude that nature, in all its diversity and uninterested in subsuming itself to the simpler organizing phenomena favored by scientists, such as synchronization, in fact revels in spatiotemporal metastability.

Keywords Broken symmetry · Multiscale · Multi-agent · Spatiotemporal · Metastability · Extended HKB · Weak coupling · Complexity

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48.1 Introduction

Living systems carry a complexity the understanding of which represents an enormous challenge to experimental and theoretical science. The aspiration persists though that eventually those systems will find their fundamental laws, the “Newtonian breakthrough” of complexity (e.g., [1–6]). Complexity science has recognized that interactions play out between elements at the same level of description but importantly also across levels [7–12], both within and across system boundaries. Accordingly, to reach the goal of finding laws of complex living systems, paradigms are required that look beyond domain-specific characteristics, so that all levels may fall under the same investigational scope.

Dynamical approaches have the ability to unite multiple levels of description in a single language, because they focus on *flows*: mathematical formalisms are not restricted to domain-specific phenomenologies, nomologies, and incommensurable quantifications. The dynamical perspective also gives due respect to adaptation [13–15, 49] and exposes processes [9, 16–20]. Useful empirical efforts include the measurement of state variables continuously [21, 22] and ideally at multiple levels of description [11, 23–27]. A striking property of living systems seems to be the emergence of functionality [16, 28–30]. Because functions emerge from interactions [30], a specific dynamical approach was developed to emphasize how the dynamics of coordinative states emerge from the parts’ coupling and symmetry [9, 31]. The work presented hereafter – examining collective dynamics of a variety of systems – is inscribed within this theoretical framework of coordination dynamics [9, 32]. Examples are examined to underline the common phenomenology across all levels, especially the concept of metastability [33]. Current research expands on earlier neurocognitive and neurobehavioral work [34–36] but shifts the focus from time to space-time (see also [30]) in order to more fully grasp the complex interplay of multiple parts. The pervasive phenomenology of metastability in nature and its interpretation via mathematical/computational models are cues toward fundamental laws of coordination in living systems.

48.2 Coordination Dynamics of Fireflies

When the coordinated patterns of male firefly flashes in trees from Thailand was documented (e.g., [37, 38]), the phenomenon became a poster child for synchronization [39]. Here we take synchronization, not loosely but within its formal definition that components lock their phase to each other (e.g., [9]). Mathematically, that requires attractor(s) [9, 17, 35]. Figure 48.1 shows a spatiotemporal analysis of fireflies, *Photinus carolinus*, that were video-recorded in the Smoky Mountains, USA. A Raster (Fig. 48.1a) and flash density plots (Fig. 48.1b) reveal their collective flashing at a strikingly regular period of about 1 Hz, whose emergence is the outcome of many fireflies’ behavior. But the details of fireflies’ spatiotemporal dynamics are more nuanced than synchrony.

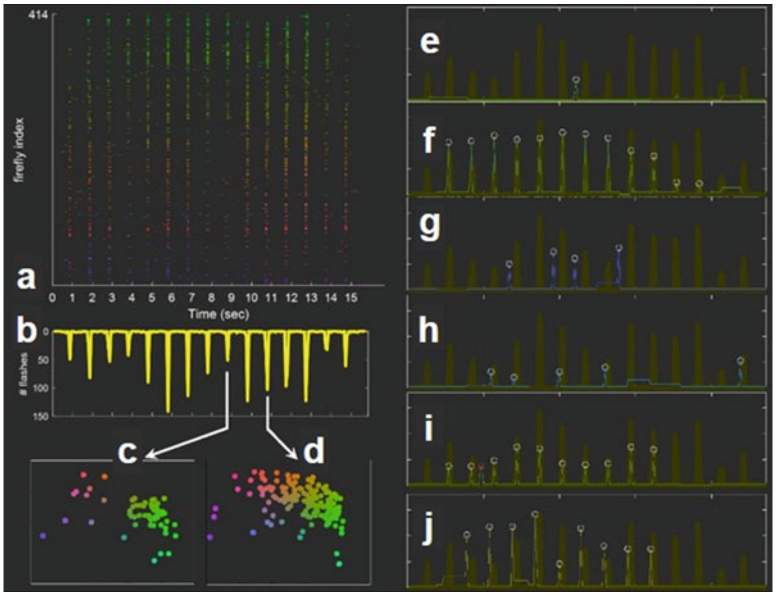

Fig. 48.1 Coordination dynamics of firefly flashes carries the hallmark of metastability. A raster (**a**), flash probability density (**b**), and spatial maps of flash events (**c**–**d**) demonstrate a spatiotemporal dynamics that has more complexity than (attractor-based) synchrony. Examples of individual behaviors (**e**–**j**) recognize that the coupling between individual and collective behavior is weak and presents key attributes previously seen in metastability, including bistable tendencies, dwell-escape dynamics, and broken symmetry. See details in text

Ensembles of fireflies vary in size over time, from small (Fig. 48.1c), with e.g., 1/8 of the population partaking in an event, to large (Fig. 48.1d) with almost a third participating, as revealed by spatial maps and analysis of flashing events. Individuals firefly behavior (e.g., Fig. 48.1e–j, bright lines representing luminance of individuals over time – for reference, the thick brown line indicates flashing density of the population as in Fig. 48.1b) varies from single contribution (Fig. 48.1e) to sustained (Fig. 48.1f, i–j) and sporadic behavior (Fig. 48.1g–h). At the temporal scale of this sample observation, phase coordination patterns tend to in phase (Fig. 48.1f), but also to a lesser extent antiphase (Fig. 48.1e.g.,), and out of phase coordination (Fig. 48.1h).

Dwell-escape dynamics (Fig. 48.1i, notice that most flashes align to the collective behavior, and one extra flash occurs, marked red, putatively releasing the intrinsic tendency to flash faster than the group) and quasi-unlocked coordination (Fig. 48.1j, notice individual flashing is slower than the group, and initial phase-lead gets smaller, as if group and individual just follow their own pace without influencing each other) are also observed. These behaviors are compatible with an underlying spatiotemporal dynamics that is metastable (see also [30]).

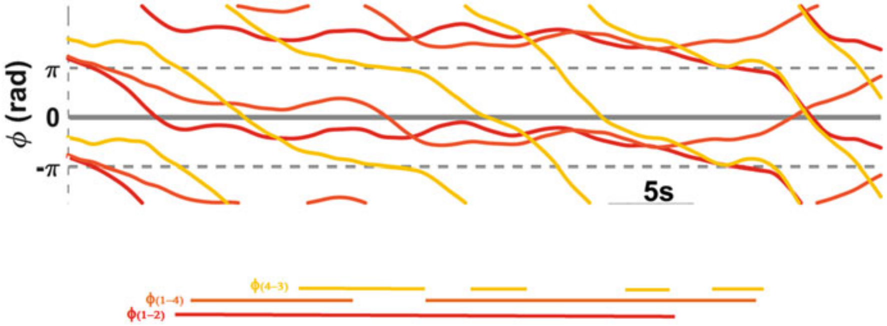

Fig. 48.2 Coordination dynamics of multiple people engaging in a sensorimotor coordination task reveals the dwell-escape coordination dynamics characteristic of spatiotemporal metastability. The relative phase of four participants (three dyads) is shown on top. Markers on the bottom indicate the location of dwells in the relative phase

48.3 Spatiotemporally Coordinated Human Behavior

To explore the possible generality of spatiotemporal metastability, we studied sensorimotor coordination among groups of eight people who sat at booths around an octagonal table. People faced an array of LEDs to see their own and others' behavior, using a touchpad to flash one of the LEDs (a human "firefly" experiment, Fig. 48.2, [40]). Human behavior was less periodic than fireflies' but otherwise revealed similar phenomenology, that is, bistability, attracting tendencies, and metastability [41]. In an exemplary trial, pairwise relative phases between four people that coordinated with each other showed dwells that persisted for longer (red) or shorter durations (yellow) and, accordingly, ensembles that included more or fewer participants over time (see also Fig. 48.1 in [25]). The dwells (horizontal segments of the relative phase) were interspersed with escape (wrapping), a hallmark of metastable coordination dynamics.

Quantitative analysis of 120 participants (15 groups, not shown) revealed some attracting tendencies, mainly near inphase, and in a selective analysis of the strongest instances of coordination, some bistable tendencies near inphase and antiphase that echoed the essential bistable tendencies observed in the brain and behavior [30, 36, 42–44]. These data suggest that just like fireflies, multi-agent human sensorimotor coordination exhibits spatiotemporal metastability.

48.4 Discussion

Examples of social behavior – from fireflies to humans – share common features with the spatiotemporal coordination dynamics of the brain, from microscale to macroscale [30]. In particular, the existence of metastability and tendencies for synchronization within as well as across frequency bands is ubiquitous [17, 30,

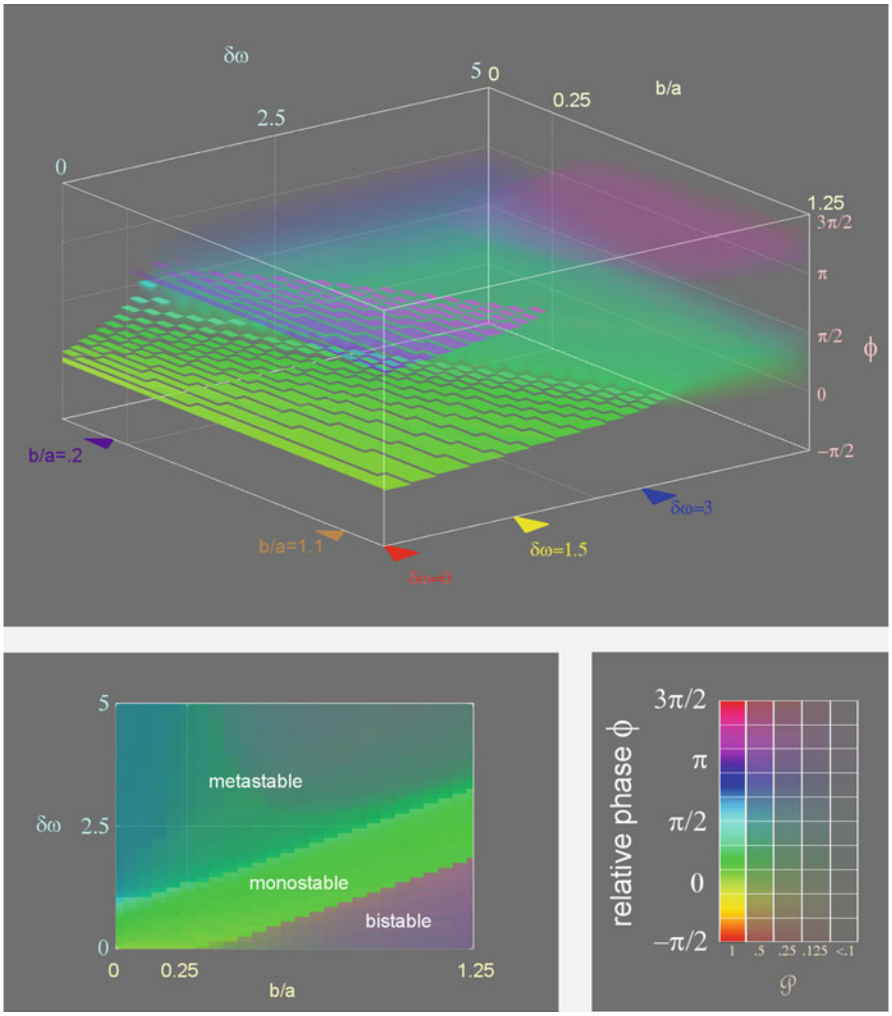

Fig. 48.3 Side view (upper panel) and top view (lower left) of a parameter space for the extended HKB model from [47], whose relative phase probability density has been encoded according to the legend on the right. Metastability emerges for weak coupling (b/a → 0) and broken symmetry (δω large)

45, 46]. Models of coordination dynamics such as the extended HKB model [47] posit two key factors that drive the dynamics of metastability (Fig. 48.3): one parameter, δω, specifies a difference in the components' intrinsic frequencies (how diverse are the self-sustained oscillators when left to themselves) and the other, b/a, expresses the coupling strength binding the components together (how intense their mutual "pull" is on each other's dynamics). Both factors play into the opportune disappearance of attractors: for example, when coupling is weak and components are diverse, metastability emerges.

Starting from empirical investigations of synchrony [16, 30, 34, 36], an easy phenomenon to query [17], we have now accrued evidence that metastability is common, if not pervasive (see also [30, 36, 45, 48]). It is likely that we only notice metastable dynamics when it possesses a striking symmetry. As a consequence much of the less orderly collective behavior typical of complex systems is misclassified. On the other hand, it is also possible that epochs appearing as synchronized are decontextualized from their broader dwell-escape dynamics due to finite windows of observation.

Once recognized, pervasive spatiotemporal metastability should not be all that surprising. Nature has many parts interacting at multiple levels, each with distinct properties often weakly coupled. According to coordination dynamics, such conditions are both necessary and sufficient for the emergence of metastability. We have suggested elsewhere that delays in appreciating the full scope of metastability may be due to methodological biases that tend to sweep dwell-escape dynamics under the rug of quasi-synchronization [17]. A common phenomenology governing the collective behavior of neural, behavioral, and social systems at multiple levels is one small step toward the formulation of laws of complex living systems. It is hoped that such yet-to-be-discovered laws open up useful generalizations for cognitive and social neurodynamics.

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