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ORIGINAL RESEARCH

Interactive agential dynamics

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Abstract

The study of active matter systems demonstrates how interactions might co-constitute agential dynamics. Active matter systems are comprised of self-propelled independent entities which, en masse, take part in complex and interesting collective group behaviors at a far-from-equilibrium state (Menon, 2010; Takatori & Brady, 2015). These systems are modelled using very simple rules (Vicsek at al. 1995), which reveal the interactive nature of the collective behaviors seen from humble to highly complex entities. Here I show how the study of active matter systems supports two related proposals regarding interaction and agency. First, I argue that the study of interactive dynamics in these systems evidences the utility of treating interaction as an ontological category (Longino, 2021) and challenges methodological individualism as the received explanatory primitive in the study of agency. Second, the methods used to research active matter systems demonstrate how a minimal approach to agency can scale up in studying interactive agential dynamics in more complex systems. The examples of coordination dynamics (Kelso, 2001) and participatory sense-making (De Jaegher & Di Paolo, 2007) are provided to show how understanding agency requires us to look beyond the individuals to the interactive agential dynamics that can guide, scaffold, or constrain their activity.

Keywords Agency · Interaction · Active matter · Explanation

1 Introduction

Active matter systems are comprised of self-propelled independent entities which, en masse, take part in complex and interesting collective behaviors at a far-from-equilibrium state (Menon, 2010; Takatori & Brady, 2015). The fundamental force

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driving active matter systems derives from expenditure of energy at the level of the individual units involved, whether these are living entities (starlings, fish, insects) or non-living objects (Janus particles, microtubules). Collectively, these individual entities, ranging from sub-cellular molecular structures to organisms with complex individual repertoires of behaviour, generate interesting macro-scale patterns of activity such as swarming, flocking, and schooling, responding to environmental features, such as external gradients, and navigating environmental perturbances. Their collective behaviors can often be modelled using very simple rules, regardless of whether the individuals involved are highly complex or simple entities.

Here, I examine the interactive dynamics within active matter systems to motivate consideration of interactive regularities in looking at agency. In the philosophy of cognitive science, there is an increasing focus on understanding the role that interactive dynamics play in shaping or even constituting cognition. For cognitive individuals, collective activities are often referred to as providing scaffolding or constraints on individual cognitive processes. Collective dynamics are explored in a number of scientific research programs: coordination dynamics (Kelso, 2021; Kelso et al., 2014) and collective behavior (Handegard et al., 2012; Couzin, 2018), for example. Several models have been created to examine and explain the interactions that lead to collective patterns of activity, such as the Haken-Kelso-Bunz model of synchronization (Haken et al., 1985) in human dyadic coordination. All of these research programs study interactive cognitive dynamics between at least two agents, where explanations of coordination are not thought to be reducible to the agents themselves nor fully captured by examining collective properties.

Using examples from active matter, I argue that likewise, in the study of agency, we ought to pay more attention to the agency-shaping properties of interactions. It is often taken for granted that much collective behavior must be explained through the attribution of complex cognitive capacities. In contrast, I will show how the study of active matter systems demonstrates that we can get more explanatory mileage when we view agency in a far more deflated and broad sense: an individual who is the causal source of asymmetry in differentiating itself from and acting towards its environment. This enables us to rethink agents and agency as a source of activity without necessarily invoking cognitive processes, though we can do so when these richer non-cognitive explanations are insufficient.

To understand agential behaviors, it is important to look beyond individual agents to the *interactive agential dynamics* in which they are enmeshed. I define interactive agential dynamics as mutually dependent, multi-agent processes that scaffold or constrain agency, in which an individual agent directly participates but does not (wholly) self-produce. These interactive processes are sustained by individuals in a group but cannot be explanatorily reduced to the activities of those individuals nor attributed to any emergent properties of the group as a whole. The agents involved directly participate in the activities that sustain the group behavior, and the interactive behavior is necessary (though not sufficient) for explaining the activity of the individuals.

While active matter systems are only one class of collective or complex system in which we find interactive agential dynamics, these systems aptly demonstrate the necessity of paying more attention to the kinds of interactive regularities shaping individual agency at a number of scales. The argument is structured as follows. Section 2 provides some background on active matter systems and the study of collective behavior. In Sect. 3, I examine some ways of taking up interaction as a non-reducible object of research. Section 4 argues that a minimalist approach to agency is most useful for looking at interactive agential dynamics. These dynamics are explored in Sect. 5 in regards to some contemporary approaches to cognition that provide purchase on inter-individual interactions. I then conclude the paper with a brief discussion of how this definition might be useful for thinking about inter-scale interactions and agency. My goal is to motivate more research on interactive dynamics in explanations of agency at all scales, and to challenge methodological individualism as the assumed explanatory priority.

2 Active matter systems

Active matter systems are “a distinct kind of nonequilibrium system” (Ramaswamy, 2017, p. 2) made up of independently active entities that collectively engage in interesting patterns of activity. A nonequilibrium system is simply a system engaged in activity sustained by energy flow into and out of the system. All living organisms are non-equilibrium systems sustained by metabolic energy processing. Some non-living entities, such as motile oil drops (Hanczyc, 2011, 2014) and Janus particles (Meredith et al., 2021)--microparticles with two physically or chemically distinct surfaces enabling a single particle to have two differing chemical reactions–can also be out of equilibrium due to self-catalyzing reactions.

The activities of active matter are often examined through physical models employing a limited set of variables, interactions, or rules (often shorthanded as *minimal models*). Though the individuals that make up active matter systems can range from sub-cellular molecular structures to organisms with complex behavioral repertoires, models of these systems typically ignore the individuals’ complexity and material differences. Some minimal models of flocking behaviour can be used whatever the flocks consist of, be it nanoparticles, birds, or bacteria. For example, the most widely-used two-dimensional model of this kind is known as the Vicsek model (Vicsek et al., 1995). Vicsek models are minimal models used to study the phenomena associated with the collective motion in active matter from complex biological to simple inorganic systems. The simple mathematical model has many individual particles which change the direction of their movement depending on the direction of their neighbors (Matsuda et al., 2019). The model, in its simplicity, shows that flocking behaviors can arise from self-propelled particles observing very basic alignment rules. With just the trademark motility of individual units of active matter systems and a mechanism for alignment, Vicsek models demonstrate that different spatiotemporal patterns of activity can be achieved with simple modulations of population density or slight alterations of the alignment mechanisms.

In animal groups, collective motion such as starling murmurations, fish schooling, and wildebeest migrations arises from repeated local interactions (Couzin, 2009). Interacting living individuals with local sensing abilities are said to follow a small number of behavioral rules: collision avoidance, velocity matching, and flock centering (staying near to flockmates) (Reynolds, 1987) that lead to alignment. This enables collective behaviors such as the amplification and dampening of collective responses, where rapid information sharing is possible through the motions of a few individuals. For example, if a few members of a traveling group perceive a predator and alter their direction of movement, that motion quickly ripples through the group, resulting in a relatively quick change in the group's trajectory. Where these kinds of activities in living groups are often thought to rely on various cognitive dynamics, such as memory and anticipation for projecting a course of motion, studies have shown that vision or vision-like perception alone and response to instantaneous cues can produce many of the complex features of flocking (Barberis & Peruani, 2016; Velasco et al., 2018). This means that even without the complex cognitive rule-following attributed to individuals in living active matter systems, we still find similar collective activities governed by local interactions.

Another important influence on the behavior of active matter systems is density. With *E. Coli*, for example, the characteristic motion of individual bacteria is the run and tumble motion. When in large groups, we see interesting collective patterns of motion occur. Well-fed dense collections of *E. Coli* will display turbulent motion, swimming in random or chaotic patterns. However, in less dense starvation conditions, the bacteria will self-organize into bands around the edge of a dish (Budrene & Berg, 1991). Examining how these kinds of changes in density impact phase transitions or rule-following behaviors is important for researchers theorizing about the functional qualities of collective activities in groups of organisms. Non-living active matter systems, though, have been shown to engage in many similar activities as their living counterparts–such as organizing into bands around a boundary (Thutupalli et al., 2018). Non-living groups have also been shown to be able to follow thermal gradients (Meredith et al., 2021) as well as navigate obstacles (Bechinger et al., 2016). As we find similar patterns of collective behavior in groups across the phylogenetic landscape as we do on the sub-cellular and nanoscale, this suggests that these living systems may actually be exploiting similar interactive regularities as found in the non-living groups.

Interestingly, explanations for *how* local interactions lead to collective behaviors are quite different for non-living active matter systems. Collective behaviors are described by appealing to general regularities involving alignment and speed within a defined area (Velasco et al., 2018). Explanations for these behaviors shift away from rules individuals follow and their functionality (e.g. the importance of information transfer or food distribution) to the properties of interactions themselves and the specific laws governing them, such as continuum field theory or Brownian motion (Gompper et al., 2020). Local alignment for some non-living collectives can be evaluated in terms of steric interactions, which concern only the attraction and repulsion dynamics that take place between individuals of certain material or chemical makeups. Modeling has shown that even a system with interactions governed only by repulsion dynamics can still engage in interesting patterns of collective behavior by forming clusters (Fodor and Marchetti, 2018). Local jamming of self-propelled elongated particles can result in alignment, or this can arise from steric interactions due to chemical reactions between materials (Velasco et al., 2018).

We might think, and often do, that to explain the coordinated behaviors of living active matter systems, we will need to draw on an extensive list of internal dynamics (e.g. memory, anticipation, leader-following, and/or rule-following). The study of interactive dynamics in non-living active matter systems shows that we might overestimate the amount of cognitive work needed in order to get interesting collective behaviors, as “[t]he bottom up, self-organized nature of collective behavior means that the group is regulated and maintains coherence without the need for any individual to have global information about the state of the others–and thus serves as a robust model of distributed control with limited communication or information sharing” (Ouellette & Gordon, 2021). Current research through models and non-living active matter systems reveals the emergence of interesting collective patterns and behaviors even when individual members have severely limited capacities. While this certainly raises some interesting questions about when, and to what extent, cognitive processes are needed as explanatory variables to understand some kinds of collective activity, I want to focus on how this research highlights the importance of interaction itself and the role that interactive dynamics might be playing in governing the activities of individual agents.

In order to research these kinds of interactive dynamics in more complex systems, we first have to take interaction to be a viable object of study. In the following section, I support this claim by showing how Vicsek models have been used to explore the effects of noise on collective activity. This provides an example of an interactive phenomena that scales up for complexity, and where the interaction itself can be treated as an object of analysis.

3 Interaction and reduction

Helen Longino has recently argued that an ontologically pluralistic approach to behavior is needed, one that includes not only the individual and the collective in explanations, but also treats interaction itself as a suitable object of research (2020, 2021). Longino points out that many of “the questions we ask already presuppose an ontology” (2021, p. 14), which is implied in the way these questions carve out phenomena in need of an explanation. The ontological framing in these questions frequently involves an implicit commitment to methodological individualism, as the questions posed seek answers that emphasize the individual at the exclusion of interactive and collective aspects of behavior. Longino proposes that by treating interactions as a viable metaphysical object of study, we expand the breadth of questions we can pose about phenomena and encourage new types of answers as well. A look at contemporary research on active matter systems demonstrates the value of this kind of ontologically pluralistic approach.

First, though, while using physics to get a better understanding of collective behavior might seem to be a boon for other fields, there may be hesitance because of lurking concerns about reduction. Perhaps this is warranted, as this research has been characterized as aiming “to bring living systems into the inclusive ambit of condensed matter physics, and to discover the emergent statistical and thermodynamic laws governing matter made of intrinsically driven particles” (Ramaswamy, 2017, p. 3). Identifying, modelling, and creating synthetic active matter systems has been thought to hold the promise of a theory of living active matter dynamics that can utilize the same formulas–such as those from mechanics and statistical mathematics–used for understanding the collective activity of non-living particles.

However, this does not mean that the study of active matter should be viewed as reductive in spirit. To draw again from Longino, what we want to know will determine which characteristics at each scale will be valuable (2021). For example, to study the collective properties of cell movement at the tissue scale, only a generalization over interactions is needed, not details about the properties of individual cells (Green & Batterman, 2017). That is, in doing multi-scale modeling, we are not trying to answer all possible questions on all scales at once. Rather than making a case for reduction, where the theories governing the inter-scale dynamics of the target system can be reduced to statistical or mechanical explanations, it is more appropriate to think of these as establishing individual, interactive, and collective regularities whose effects can be tested within the broader system. The formalizations derived can also be helpful for understanding the additional variables that need to be included when we scale up to more complex systems (McGivern, 2020). These assist in determining what formalizations, regularities, and behaviors are scale invariant and which are scale-specific.

Using models to find formalizable regularities, whether scale-specific or scale invariant, need not have anything to do with reducing macro-scale explanations to the micro-scale. Model selection is highly dependent on both the type of behavior being modeled and in what context that behavior is occurring. Researchers studying active matter must be very precise about the difference between individual, collective, and interactive variables and explanations, as well as their limitations. For example, Sinhuber et al. (2021) have developed a thermodynamic descriptive framework for collective group activity, which provides state equations for midge swarms (small flies) in order to investigate the collective function of their group behaviors. They are careful to avoid implying that these state equations could provide interactive rules that would also apply on other scales, in other models, or in other contexts: “Extracting interaction rules by observing group behaviour is a highly non-trivial inverse problem that can typically only be solved by assuming a modelling framework a priori. Appropriate model selection is made more difficult given that interactions may change in different contexts” (Sinhuber et al., 2021, p. 1). State equations useful for understanding midge swarms would not necessarily be useful for understanding interactions governing collective behaviors found in other groups, even if similar interactive regularities are present. In sum, the descriptive framework used for understanding the function of the collective behavior reduces to neither the interactive nor the individual domain.

Likewise, inter-individual interactions are often thought to reduce to individual contributions (Longino, 2021). Vicsek models provide a simple example of how inter-individual interactions can be given a distinct treatment. In Vicsek models, each agent in the model averages its current heading and velocity in accordance with its local neighbors at regular intervals. These two interactive rules are enough to lead to collective behaviors (swarming, flocking) in the system. Of course, in real systems, there may be internal or environmental features that interfere with alignment, so Vicsek models are also used for studying the effects of noise on the system’s collective activity. Noise can be divided into two kinds: intrinsic noise, which disrupts the internal alignment mechanism, and extrinsic noise, which causes difficulties in the alignment process itself (Chepizhko & Kulinskii, 2010). For models of living active matter systems, such as a fish school or starling murmuration, extrinsic noise represents factors that affect conspecifics' alignment interactions, such as fog, or murky water; for bacteria or particles, it might be a chemical interference introduced into the colloidal medium. Noise might also involve physical interferences such as topological defects or vibrations, such as sound waves. At a certain level of noise, the group will go through a phase transition wherein the orderly (aligned) system will become disorderly (random movement) or vice versa.

Because "the motion of flocking organisms is usually controlled by interactions with their neighbors" (Czirók & Vicsek, 2000, p. 18), noise is used to test interaction variability and strength. Each agent in a Vicsek model is following the same alignment and velocity matching rules; these are ongoing interactive processes that necessarily depend on more than one agent. By altering noise, researchers have interventions which allow them to test the strength and variability of these interactions. The noise that intervenes on the interactions can be adjusted to examine how active matter will move in different mediums or under different boundary conditions "when the level of *pertubrations* or the mean *distance* between the individuals are changed" (Czirók & Vicsek, 2000, p. 17). Variables and inputs can be altered to test the scale-specificity of interactions, as "such models represent a statistical approach complementing other studies which take into account more details of the actual behavior" (Czirók & Vicsek, 2000, p. 18). This can reveal aspects that are important for understanding how these interactions underpin macro-scale behaviors at another scale, including some of the fundamental processes of cellular life (Doostmohammadi et al., 2018), without reducing explanatorily to either collective or individual activity.

These models can also be adjusted to evaluate how the density and boundary conditions influence interactive dynamics. For example, Thutupalli and colleagues used different boundary conditions to test the collective behavior of oil droplets in hydrodynamic flow fields (Thutupalli et al., 2018). They found that within a tight boundary, the oil droplets would briefly form into unstable bands and then scatter. When the boundaries were farther apart, the oil droplets formed into stable bands that not only maintained their coherence but could travel through other bands traveling the opposite direction and re-form. With one boundary wall removed completely, the oil droplets continued to form into collectives and, depending on whether the wall was replaced with water or air, they would engage in a schooling-like behavior or would form small semi-stable two-dimensional groups. Stokes flow equations are used to calculate the force of flow fields exerted by droplets in these boundary conditions, providing a picture of the ways that the hydrodynamic flow operates around individuals. However, to understand how the individuals engage in the collective activities they do, the pair interactions have to be mapped out in terms of flow-induced phase separations. In other words, this is another example where interactions themselves are treated as a difference-maker. Understanding the collective behavior involved not only treating the interactions as the focal point of interest, but also treating the material design of the surroundings (boundaries) as a parameter *of the interaction* rather than as a parameter of the individuals involved.

As the previous section argued, cognitive capacities tend to be over-invoked in explanations of group behaviors that involve complex individuals. The examples in this section show how interactions themselves play a role in organizing group behaviors and are already considered points of intervention in the study of active matter systems. In the next two sections, I use this evidence for the importance of interaction for thinking about agency. The study of agency is, likewise, highly methodologically individualistic. While individual-scale explanations are important, we have largely overlooked the ways that individuals are often enmeshed in interactive dynamics which constrain or scaffold what we find at the individual scale.

4 Agency and interaction

Many of the conceptions of agency we find in the philosophical literature are both human-centered and methodologically individualistic. If we are looking to understand or make claims about rational agency, moral or legal responsibility, or other concerns relevant to human forms of life, then this is often appropriate, but recent decades have also seen a rise in foundational biological or organizational criteria pointed to as hallmarks of an agentive system. Several developing research areas, such as basal cognition (Lyon et al., 2021) and autopoietic enactivism (Varela et al., 1991, Barandiaran et al., 2009), treat agency as inherent to all living systems.

Regardless of the recent shift away from intellectualism about agency, looking at how interactive dynamics shape agency is tricky, as definitions of agency are still specific to theoretical frameworks. That is, definitions of agency are most commonly generated with a specific framework for understanding behavior and/or cognition in mind (e.g. computational, information-theoretic, autopoietic, and so on). Given this, the methodological individualism we find in definitions focused on demarcating agential from non-agential individuals is not necessarily problematic. Defining what makes something an agent (and other things non-agents) requires claims about an individual. But we do not just want to know what an agent is; we also want to know how agency works, and explanations focused solely on the individual do not give us the whole story.

Fortunately, the previous sections have demonstrated that getting a firm grip on what exactly an agent is (or is not) through a precise cognitive criterion is neither necessary nor explanatorily useful for the project of establishing interactive regularities. Interactions do not always reduce to the contributions of individual agents, and can be inexplicable in terms of collective properties as well. We can thus leave it an open question what criteria should be used to distinguish cognitive agents from non-agents, as this is a framework-specific question. In fact, we will not need to connect agential dynamics and cognitive dynamics at all.

The more one loads up a definition of agency with cognitive criteria in order to exclude this or that kind of entity (plants, bacteria, artificial intelligence), the more difficult it is to establish regularities in interaction. A suitable pre-theoretical approach would define an agent as an individual with some capacity for activity. This is the conception at work in the terminology of "Brownian agents" (Schweitzer, 2003) or "particle agents" (Ebeling & Schweitzer, 2001) used to indicate entities that at the very least have the ability to initiate or maintain activity through the expenditure of their own energy. Another good pre-theoretical definition comes from Stuart Kaufmann, who defines autonomous agency as “a self-replicating system that is able to perform at least one thermodynamic work cycle” (Kauffman, 2003, p. 1090), optimistic that his definition “gives the minimal physical condition for a physical system about which the language game of doing, acting and value becomes natural” (ibid.). While this definition is still loaded in other, non-cognitive ways, what is important is that it is clear that what makes the dynamics *agential* rather than *cognitive* is that the individuals engage in activity by using their own energy. Additional cognitive (or other) variables can be added as needed when interactions grow more complex.

The pre-theoretical definition of agency proposed is useful for looking at interactive regularities on all scales because it does not involve drawing a hard line between behavior and mere activity, as the important factor is that the agent is energetically responsible for its own movement. As we see with active matter systems, there is an interesting grey area here precisely because of the interactive dynamics that can make collective activity non-random even for non-living systems. In this way, looking at interactive dynamics can be an altogether different (though supplemental and supporting) project from determining agential capacities and determining to which organisms or systems they belong. The utility is in setting aside unnecessary questions about individual capacities when we are looking specifically at interactions.

Conversely, explaining why an individual organism engages in a behavior might involve establishing fundamental processes of self-organization, positing internal dynamics, situating the organism within its environment, looking at the organism’s adaptive learning capacities, and so on. We might take into account whether the system is goal-directed, or can be thought of as having intentions. And any scale-specific definition of agency will also be subject to debates about the most suitable theoretical framework. Taking a non-autonomous approach to agency as a means to look at interactions does not restrict how we understand individual agency. Further, other aspects of agency may be important at particular scales, and we might consider how or whether the inclusion of additional agential dynamics for individuals affects the scale-dependency of interactions at that scale. For looking specifically at interactions, our operationalization of agency ought to reflect its utility across a variety of research programs, rather than tracking our metaphysical commitments or intuitions.

I have argued that a pre-theoretical definition of agency is most productive for looking at the interactive regularities that can shape activity. All that we need be concerned with for looking at interactive regularities is that an agential entity generates its activity rather than being fully at the mercy of external forces. The advantage of this terminology is that it carves out an interdisciplinary space for looking at interaction, and second, that it does not posit any cognitive capacities to the individual agents that make interaction a more appropriate phenomena of study for one discipline over another. To look at how they influence agency, interactions are treated as contracting or expanding degrees of freedom for action, thus facilitating the undertaking of actions that would otherwise not be available or limiting actions that would otherwise be available. The aim is to understand agency better, where agency involves energy exertion within a limited range of degrees of freedom, by asking what degree-of-freedom-establishing forces belong to the interaction itself. Simply by asking a question in this manner, by treating the interaction as subject to intervention, we are afforded the opportunity to operationalize and empirically test the interaction itself (coupling strength, density thresholds, etc.) in obtaining an answer.

Importantly, this does not require that we commit to the existence of an interaction in a metaphysically robust sense, just that we treat it epistemically as such. In the following section, I offer some examples from theoretical and empirical cognitive science that treat interaction itself as a viable ontological proprietor of cognition-shaping processes. These illuminate how we might approach formulating questions about agential scaffolding and constraints.

5 Interactive agential dynamics

In this section, I offer some suggestions for formulating questions on interactive agential dynamics in studying agency and cognition. Interactive agential dynamics can be defined as mutually dependent, multi-agent processes in which individuals directly participate that may guide, scaffold, or constrain agency. To clarify, this is not about describing activities that individuals engage in together (e.g. joint action), but about understanding how interactive processes and regularities between individuals establish scaffolding and constraints for behaviors. I consider these to be mutually dependent in the sense that they are sustained by individual agents but cannot be explanatorily reduced to the activities of individuals nor attributed to any emergent properties of a group. The agents involved directly participate in the interaction, and the interactions are necessary (though not sufficient) for explaining the activity of the individuals. In order to understand the kinds of internal dynamics involved with agential behaviors in biological agents, the previous section argued that we start with individuals with a capacity for action participating in activities that involve interactive dynamics, but in which there is no need to posit any further internal dynamics to the system (regulation, decision-making, or goal-directedness). Such additional dynamics can be incorporated as they become necessary to explain more complex interactive behaviors.

In previous sections, I have provided some examples of how interactive dynamics are taken up in the study of non-living active matter systems. What might we learn about agency from looking at the interactive dynamics of these kinds of systems, and how might we similarly ask about interactive agential dynamics for more complex or cognitive agents? There are several areas of cognitive research that utilize theories or models to look specifically at interactions, of which I will go over but a few. There is the burgeoning field of interaction studies itself, for example, but this field is united topically, not as a unified research program. More specifically within cognitive science, there is Bickhard's interactivist approach to the study of the mind (2009), which reimagines mental representations within an interactive view of process metaphysics. There is also work by Seibt (2009) on how we might logically schematize types of emergent interactions.

One theory that has stressed the importance of viewing agency through an interactive lens is Latour's Actor-Network Theory (ANT) (Latour, 1996). ANT is too complex to detail here, but the relevant aspect is that it is a sociological approach to agency in which individuals are taken to emerge from interaction, a radical shift from treating interactions as taking place between pre-given individuals. As Latour describes it, one of the preoccupations of ANT is “an ontological claim on the ‘networky’ character of actants themselves” (1996, p. 373), where actants “can literally be anything provided it is granted to be the cause of an action” (ibid.). Rather than involving methodological individualism, Latour’s theory goes to the opposite extreme in espousing methodological reduction to local networks (1996). On his view, agency must be viewed through a metaphysical lens in which interaction is the only viable category for underpinning explanations. Bennett (2010) and Malafouris (2013) have both expanded on ANT in ways that include the material environment in the networks from which agency emerges.

Decades of work now in enactive, extended, and embedded cognition, as well as ecological psychology, likewise argue that an exclusive focus on internal dynamics keeps us from appreciating how cognition is structured by (or constituted within) the agent-environment relationship (Clark, 2016; De Jaegher, 2018; Gibson, 1979; Paolo et al., 2017; Thompson, 2007; Varela et al., 1991). In the enactivist approach in particular, cognition is conceptualized as a dynamic interactive process involving the agent-environment system. Enactivists are committed to the best explanation of cognition involving processes across the agent-environment system, though this doesn’t necessarily require committing to a robust metaphysics involving these categories (Chemero, 2009).

While the environment has been taken up as co-determining the realm of possibilities for a particular agent, ultimately it is not clear why stressing the agent-environment relation in this way is not still utilizing a kind of methodological individualism. The inclusion of interaction is intended to flesh out the story of individual cognition, perception, and/or subjectivity, through looking at cognition as an environment-inclusive process. That is, enactivism as a framework does not necessarily view interactions as an object of investigation, though cognition is expanded *interactively* beyond the individual. For the most part, the cognitive agent (or agency) is conceptualized in a situated, active sense–but the goal is still to provide answers to questions about cognition at the individual scale. In this way, “proponents recognise the need for a perspective change that does proper justice to the situatedness and embodiment of the social subject, [but] often remain themselves methodologically individualistic” (De Jaegher & Di Paolo, 2007, p. 486). While the enactive approach moves away from treating cognition as internal to the system to conceptualizing it as an (inter) active process spanning more than the individual organism, it is still at its core a methodological individualism in that the explanandum is cognition at the individual scale. The interaction processes themselves in which individuals engage are simply part of the explanans.

One exemplary exception is the enactive theory of *participatory sense-making* (PSM), which holds that a social interaction involving two or more agents can itself be considered an autonomous process (De Jaegher & Di Paolo, 2007; see also De Jaegher & Froese, 2009). PSM was developed in response to the limitations of the pervasive methodological individualism for understanding social cognition. Briefly, social cognition is the ability to understand what another is feeling, wanting, thinking, or intending, and the cognitive underpinnings of these abilities are a hotly debated topic in the philosophy of cognitive science. In introducing the theory, De Jaegher and Di Paolo criticize the commitment of other approaches to explaining social cognition through appeal to individual mechanisms alone:

> "…as long as there is no explicit and focused attention to [the] relational domain … this emphasis on interaction remains vacuous. In many of these approaches, the interaction seems merely an addendum to a position that departs from what is really still an individualistic perspective. In our opinion, any approach that mentions interaction, but fails to go into the relational dynamics of the interaction process in detail, is simply not an interactive account and probably not even a social one, despite the goodwill driving it." (2007, p. 494)

In contrast, De Jaegher and Di Paolo clearly specify that "[i]nteractions depend on individual contributions, but are not fully determined by them. They depend also on the relational dynamics between subjects, and other factors" (De Jaegher & Di Paolo, 2012, p. 1; see also Auvray et al., 2006, Di Paolo et al., 2008; Di Paolo and De Jaegher, 2012). Elsewhere, they offer a clear definition of an interaction as "the mutual interdependence (or bidirectional, co-regulated coupling) of the behaviors of two social agents" (Di Paolo et al., 2010). They point out that coordination between individuals has been demonstrated not to require much in the way of cognitive capacities, which I have shown above to be the case in the study of collective behavior in active matter systems. Moreover, they note that interactive coordination is "often hard to avoid" (2007, p. 490).

De Jaegher and Di Paolo specify that a PSM interaction emerges when "social encounters acquire [an] operationally closed organization" where "the agents sustain the encounter, and the encounter itself influences the agents" (ibid., p. 492). Now, unlike some of the examples above where physical or chemical coupling leads to interesting patterns of behavior, at the more complex organismic levels the individuals have to exert energy to maintain the social interactions in PSM. This explains why PSM takes on additional individual considerations, such as maintaining individual autonomy and sustaining motivation to perpetuate an interaction. What De Jaegher and Di Paolo stress is that what makes this particular kind of interaction *social* is the preservation of the autonomy of the interacting agents–the agents must be actively contributing to the interaction *and* maintaining their autonomy for it to be considered its own autonomous process (2007).

Looking at the theory of PSM draws attention to three important facets of theorizing about interactions for more complex cognitive systems, as discussed in previous sections. First, attribution of properties at the individual level only need to include what is absolutely necessary for the purposes of delineating the type of interaction. Second, the nature of the interaction–in this case, its self-organizing autonomous nature–is articulated in such a way that offers possibilities for empirical analysis of the interaction itself (whether or not the means are currently available). Third, the interaction is sustained by the energy output of the individuals involved and their degrees of freedom are limited or enabled through engagement in or maintenance of the emergent interaction. In some ways, sustaining an interaction constrains the agency of the individuals involved, but the interaction can also enable possibilities for group activity and coordination that were not previously available.

Since we are concerned here more broadly with interactive agential dynamics, there are certainly other examples of interactions between individuals that can shape the degrees of freedom of those involved. De Jaegher and Di Paolo give the example of the transfer of body heat between people at a bus stop as one example of non-social, non-autonomous interaction, where “there is coupling between the agents, but the coupling is not actively regulated by the agents involved so as to affect this coupling itself” (2007, p. 493). This would be on the lesser constraining-or-enabling end of the interaction spectrum. Nearer the other end, we find other kinds of complex social interactions, where we might need to posit cognitive capacities at the individual scale to explain regularities, such as with interactive synchrony (Varga, 2016). This term is used to describe infant-caregiver interactions where there is “an emergence and maintenance of non-predetermined synchronic interaction patterns over time, in which caretaker and infant complement each other’s states and moderate the level of positive arousal in cooperation” (Varga, 2016, p. 2474), which leads to “organization of social behaviour into rhythmic sequences” (ibid. p. 2475).

For an example of why it is important to establish minimal criteria at the individual scale when looking at interactions, let’s look at a counter-example. Satne (2021) has criticized what she views as the insufficiency of PSM in that it does not specify what kinds of agents can enter into a PSM interaction. One of the flaws in taking PSM interactions up as explanatory, Satne claims, is that “the concept of [interaction as an] ‘autonomous system’ does not yet draw differences between agents, including biological organisms and artificial ones, and persons, to whom we apply the enriched idiom of mental predicates” (2021, p. 511–512). Satne argues that interactions alone cannot constitute social cognition, and that in order for PSM to do so, it requires more demanding cognitive elements at the individual scale: an understanding of both one’s own and their interactor’s goals, as well as a shared goal of maintaining the interaction, “constituted by interactants targeting and keeping track of each other’s goals and in such manner, being attentive to other’s goal directed attitudes” (Satne, 2021, p. 523).

First, where PSM is making claims about how interactions can play a constitutive role in social cognition, Satne conflates the explanatorily relevant aspects of social cognition that exist at the individual and the interactive scales, treating the interaction as though it is intended to do individual-scale work. De Jaegher and colleagues are clear that interactions are a constitutive element in understanding social cognition, not the full explanation (2010, p. 443). They specify that interaction dynamics might, in some cases, play explanatory roles that have traditionally been ascribed solely to individual mechanisms (ibid., p. 445). Satne’s argument assumes that interactions ought to be able to do all of the work at both individual and interactive scales. This would require taking interaction in the more methodologically individualistic sense of being merely an extension of the individual. Either the PSM interaction is not being treated as an autonomous process or the process is being reduced to individual-scale explanations.

Second, the non-specificity about types of agents is clearly highlighted in PSM as a feature, not a flaw: “We do not restrict social interaction to the human species.

As long as the terms of the definition can be verified, they can apply to cross-species interactions or interactions with robots that are autonomous in the sense intended" (De Jaegher et al., 2010, p. 443). Pre-emptive exclusion of some types of agents as capable of interactions based on individual criteria closes off what might be very fruitful research avenues unnecessarily. Rather than trying to get an explanation that covers all scales at once by inflating criteria at a single scale, PSM demonstrates the use of treating interactions as separate, although enabling, constraining, and/or constitutive elements, worth taking into account when formulating full explanations.

Satne's scale equivocation, though, draws attention to a broader concern about how we delineate between processes at the individual, interactive, and collective scale. Pamela Lyon (2006) has made a similar point regarding concerns about the difficulty of demarcating cognitive processes from biological processes. She stresses the salience of this problem for organizational approaches, where operational closure of the system understands self-organizing biological processes as dynamically interwoven and co-sustaining: "What an observer designates as an organism's 'cognitive subsystems' will always have substantially linked, if not shared, molecular pathways with other systems usually considered to be non-cognitive—just as the brain, so often equated with mind, supports 'physical' functions as well as 'mental' ones, and it is difficult to determine where one sort ends and the other sort begins" (Lyon, 2006), p. 25). For understanding interactive agential dynamics, we have a comparable demarcation problem if we try to isolate the cognitive or biological processes that constitute agency to either the individual or interactive scales, not to mention macro- or micro-scales. This likewise closes off potential research avenues for understanding how molecular sub-systems self-organize and support biological processes, how interactions between non-autonomous individuals can themselves become autonomous, how these processes break down, and so on.

Participatory sense-making provides an example of how we can treat interactions as an ontological category in the study of cognition, and how we can do so in a way that is deeply linked with the empirical side of cognitive science, by drawing on dynamical systems models (DST). Another example comes from the Haken-Kelso-Bunz (HKB) model of coordination, one of the most widely used applications of nonlinear dynamical laws being used to explain behavioral coordination in biological systems (Haken et al., 1985). Coordination models are appealed to often in discussing interaction, which have been used for understanding how coupled systems, living and non-living, engage in synchronization patterns without appealing strictly to hierarchical mechanisms. Briefly, the HKB model is a model of motor coordination that tests the metastability of interactions. Though originally developed to study bi-manual coordination in individuals, the model was partly inspired by the self-organization of collective groups (e.g. bird flocks and fish schools) that we see in active matter systems (Kelso, 2001).

One of the guiding aims behind the development of the HKB model was to understand how collective behaviors can shape degrees of freedom within the collective, where the full range of activity of individuals is limited to a smaller set of dynamical variables (Kelso, 2001). The HKB model tracks phase transitions between in-phase and out-phase patterns of coordination, as well as multistability, through the use of synergetic concepts. Kelso describes this in terms of the relation of events on different timescales: “the faster individual elements in the system may become ‘enslaved’ to the slower, emergent pattern or collective variables, and lose their status as relevant behavioral quantities (Haken, 1977)” (2001, p. 13,846). To explain the relationship between these slower emergent behaviors at the collective scale and the individual behaviors, we have to understand how the collective behaviors create boundary conditions, or constraints, on the faster-timescale individual behaviors. The individual behaviors might have control parameters, which involve the range of possibilities of the individual as determined by its composition and energetic output, and these control parameters are what become limited by collective coordination. With the emergence of stability at the collective scale comes restriction at the individual scale; these collective scale constraints are order parameters.

The HKB model and its many adaptations provide means for testing coupling strength and a language for conceptualizing how local interactions can constrain and enable degrees of freedom. These models have been applied to understanding interactive phenomena, such as the sensing of coordination instabilities (Granatosky et al. 2018), coordination strength and social memory (Nordham et al., 2018), remote synchrony in motor coordination (Alderisio et al., 2017), increases in coupling strength with mechanical coordination (Cuijpers et al., 2019), and multi-agent coordination in medium-sized human ensembles (Zhang et al., 2018). Other empirical work has confirmed and/or supplemented this work, demonstrating inter-brain synchronization in social interaction (Dumas et al., 2010) and music improvisation (Müller et al., 2013).

To summarize, HKB models give us but one example of the resources available now in the cognitive sciences to provide explanations for the shaping of agency at multiple scales without focusing solely on individualistic mechanisms. These and other models have shown that interactions themselves can play both causal and constitutive roles in establishing possibilities for action (Meyer, 2020). Some of these interactive agential dynamics will involve explicit, evaluable cognitive phenomena, but many can be evaluated without invoking cognitive dynamics at all. Again, the interactions themselves can be studied and intervened upon, and provide their own explanatory value: “In short, for biological coordination, concepts from physics such as order parameters and their essentially nonlinear dynamics were shown to rule at both collective and component levels” (Kelso, 2021, p. 3). This is important for moving away from treating interactions between agents as purely involving individual mental phenomena, and makes it clearer how framing questions differently can open us to understanding how interactions situate agency by establishing some constraints and enabling conditions.

How interactive dynamics shape individual agency, whether at the cellular or social level, still remains largely unexplored. The relationships between individual, interactive, and collective scales are an additional concern which is reaching a critical point in cognitive science: “The question is what kind of framework could be put in place which will allow us to make sense of the relationships between these different scales – recognizing their differences and systematically addressing their interactions” (McGann, 2020, p. 5). However, this concern applies more broadly when we think about agential dynamics. Understanding how collective non-living activity can support macro-scale biological processes is going to require substantive work on not just collective properties, but interactive regularities. For instance, actin filaments play an important role in separating the chromatic materials (DNA) in nuclei during cell division. Here, microtubules form a network across the body of the cell, a spindle apparatus or mitotic spindle, that acts to separate the cell itself during cytokinesis (when a cell divides into two daughter cells). When extracted from cells, these same cellular components, actin and myosin filaments, will exhibit flocking behaviors in high density conditions (Schaller et al., 2010; Butt et al., 2010). Interactive forces have also been shown to play a role in collective behavior of cells in processes such as morphogenesis and collective chemotaxis (Balasubramaniam et al., 2021; Hughes & Yeomans, 2020).

While this paper has focused mostly on motivating further exploration of and research on interactions between agents, we might also think about how interactions across scales could be similarly treated as a viable category for investigation and study. To do so, I suggest, would also require that we consider interactive agential dynamics in the minimal way I have advocated for in previous sections. Locating agency at a particular scale or threshold of cognitive capacities limits our ability to understand the interactive agential dynamics that can help us make sense of the behaviors of individuals, collectives, and the scaffolding and constraints between scales. Consideration of the scale-specificity of some kinds of interactions, as well as the scale-specific manifestations of scaffolds and constraints, will point to the kinds of disciplinary resources that will be helpful for getting some answers.

6 Conclusion

In sum, I have argued that changing our ontological framing of questions around agency to treat interaction as a viable ontological category can generate new kinds of questions and answers. This includes both inter-individual and inter-scale interactions. In treating interactions as a category for inquiry, we can look at the boundary conditions of interactions themselves, we can establish how interactions scaffold and constrain activity, and we can think about how to test interactive coupling. I have also argued that this will help us solve problems in which a single-framework or phenomena-specific definition of agency is unlikely to give us much explanatory purchase.

Agents, even human agents, are enmeshed in all kinds of low-level and high-level interactive dynamics that shape their behavior. Though using formulations from physics is often thought of as being a reductive approach to understanding cognition, decades of work from coordination dynamics demonstrate that this is not the case. Looking at the study of non-living active matter can help us understand interactive agential dynamics, and can provide inroads to grasping even more interactive phenomena that shape behavior. Thinking in terms of agency rather than cognition helps us in formulating questions about constraining and enabling conditions at a multitude of scales. As Longino has proposed, treating these interactions as causally relevant ontological categories can reveal explanatorily relevant intermediaries between individual and group scales. The first step is just to start asking the right kinds of questions.

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Declarations

Conflict of interest The author declares no conflicts of interest.

References

Alderisio, F., Fiore, G., Salesse, R. N., Bardy, B. G., & Bernardo, M. (2017). Interaction patterns and individual dynamics shape the way we move in synchrony. *Scientific Reports, 7*(1), 6846.

Auvray, M., Lenay, C., & Stewart, J. (2006). The attribution of intentionality in a simulated environment: The case of minimalist devices. Tenth meeting of the association for the scientific study of consciousness, Oxford, UK, 23–26 June, 2006.

Balasubramaniam, L., Doostmohammadi, A., Saw, T. B., Narayana, G. H. N. S., Mueller, R., Dang, T., & Thomas, M. (2021). Investigating the nature of active forces in tissues reveals how contractile cells can form extensile monolayers. *Nature Materials, 20*, 1156–1166.https://doi.org/10.1038/s41563-021-00919-2.

Barandiaran, X. E., Di Paolo, E., & Rohde, M. (2009). Defining agency: Individuality, normativity, asymmetry, and spatio-temporality in action. *Adaptive Behavior, 17*(5), 367–386.

Barberis, L., & Peruani, F. (2016). Large-scale patterns in a minimal cognitive flocking model: Incidental leaders, nematic patterns, and aggregates. *Physical Review Letters*, *117 No*(24), 248001.

Bechinger, C., Di Leonardo, R., Löwen, H., Reichhardt, C., Volpe, G., & Volpe, G. (2016). Active particles in complex and crowded environments,. *Reviews of modern physics* (88 No vol., p. 045006). American Physical Society. 4.

Bennett, J. (2010). *Vibrant matter*. Duke University Press.

Bickhard, M. H. (2009). The interactivist model. *Synthese, 166*(3), 547–591.

Budrene, E. O., & Berg, H. C. (1991). Complex patterns formed by motile cells of Escherichia coli. *Nature*, *349 No*(6310), 630–633.

Butt, T., Mufti, T., Humayun, A., Rosenthal, P. B., Khan, S., Khan, S., & Molloy, J. E. (2010). Myosin motors drive long range alignment of actin filaments 2. *The Journal of Biological Chemistry, 285*(7), 4964–4974.

Chemero, A. (2009). *Radical embodied cognitive science*. MIT Press.

Chepizhko, A. A., & Kulinskii, V. L. (2010). On the relation between Vicsek and Kuramoto models of spontaneous synchronization. *Physica A: Statistical Mechanics and Its Applications*, *389 No*(23), 5347–5352.

Clark, A. (2016). *Surfing uncertainty: Prediction, action, and the embodied mind*. Oxford University Press.

Couzin, I. D. (2009). Collective cognition in animal groups. *Trends in Cognitive Sciences*, *13 No*(1), 36–43.

Couzin, I. D. (2018). Synchronization: The Key to Effective Communication in Animal Collectives. *Trends in Cognitive Sciences*, *22 No*(10), 844–846.

Cuijpers, L. S., Den Hartigh, R. J. R., Zaal, F. T. J. M., & de Poel, H. J. (2019). Rowing together: Interpersonal coordination dynamics with and without mechanical coupling. *Human Movement Science*, *64*, 38–46.

Czirók, A., & Vicsek, T. (2000). Collective behavior of interacting self-propelled particles. *Physica A: Statistical Mechanics and Its Applications*, *281 No*(1), 17–29.

De Jaegher, H. (2018). The intersubjective turn. In A. Newen, De L. Bruin, & S. Gallagher (Eds.), *The Oxford handbook of 4E cognition* (vol. 1). Oxford University Press.

De Jaegher, H., & Di Paolo, E. (2007). Participatory sense-making: An enactive approach to social cognition. *Phenomenology and the Cognitive Sciences, 6*(4), 485–507.

De Jaegher, H., & Di Paolo, E. (2012). Enactivism is not interactionism. *Frontiers in Human Neuroscience*, *6*, 345.

De Jaegher, H., & Froese, T. (2009). On the role of Social Interaction in Individual Agency. *Adaptive Behavior*, *17 No*(5), 444–460.

De Jaegher, H., Di Paolo, E., & Gallagher, S. (2010). Can social interaction constitute social cognition? *Trends in Cognitive Sciences*, *14 No*(10), 441–447.

Di Paolo, E., & De Jaegher, H. (2012). The interactive brain hypothesis. *Frontiers in Human Neuroscience*, *6*, 163.

Di Paolo, E. A., Rohde, M., & Iizuka, H. (2008). Sensitivity to social contingency or stability of interaction? Modelling the dynamics of perceptual crossing. *New Ideas in Psychology*, *26 No*(2), 278–294.

Doostmohammadi, A., Ignés-Mullol, J., Yeomans, J. M., & Sagués, F. (2018). Active nematics. *Nature Communications*, *9 No*(1), 3246.

Dumas, G., Nadel, J., Soussignan, R., Martinerie, J., & Garnero, L. (2010). Inter-brain synchronization during social interaction. *PloS One, 5*(8), e12166.

Ebeling, W., & Schweitzer, F. (2001). Swarms of particle agents with harmonic interactions. *Theory in Biosciences = Theorie in Den Biowissenschaften*, *120*(3), 207–224.

Fodor, É., & Cristina Marchetti, M. (2018). The statistical physics of active matter: From self-catalytic colloids to living cells. *Physica A: Statistical Mechanics and Its Applications*, *504*, 106–120.

Gibson, J. J. (1979). *The ecological approach to visual perception*. Houghton Mifflin.

Gompper, G., Winkler, R. G., Speck, T., Solon, A., Nardini, C., Peruani, F., Löwen, H. (2020). The 2020 motile active matter roadmap. *Journal of Physics. Condensed Matter: An Institute of Physics Journal*, *32*(19), 193001.

Green, S., & Batterman, R. (2017). Biology meets physics: Reductionism and multi-scale modeling of morphogenesis. *Studies in History and Philosophy of Science Part C: Studies in History and Philosophy of Biological and Biomedical Sciences, 61*, 20–34.

Haken, H. (1977). *Synergetics, an introduction: Non-equilibrium phase transitions and self-organization in Physics, Chemistry and Biology*. Springer.

Haken, H., Kelso, J. A., & Bunz, H. (1985). A theoretical model of phase transitions in human hand movements. *Biological Cybernetics*, *51 No*(5), 347–356.

Hanczyc, M. M. (2011). Metabolism and motility in prebiotic structures. *Philosophical Transactions of the Royal Society of London Series B Biological Sciences*, *366 No*(1580), 2885–2893.

Hanczyc, M. M. (2014). Droplets: unconventional protocell model with life-like dynamics and room to grow. *Life*, *4*(4), 1038–1049.

Handegard, N. O., Boswell, K. M., Ioannou, C. C., Leblanc, S. P., Tjøstheim, D. B., & Couzin, I. D. (2012). The Dynamics of Coordinated Group Hunting and collective information transfer among Schooling Prey. *Current Biology: CB*, *22 No*(13), 1213–1217.

Hughes, R., & Yeomans, J. M. (2020). Collective chemotaxis of active nematic droplets. *Physical Review E*, *102*(2), 020601(1–5).

Kauffman, S. (2003). Molecular Autonomous Agents. *Philosophical Transactions of the Royal Society A*, *361 Issue 1807*, 1089–1099.

Kelso, J. A. S. (2001). Self-organizing dynamical systems. In N. J. Smelser, & P. B. Baltes (Eds.), *International encyclopedia of the social & behavioral sciences* (pp. 13844–13850). Pergamon.

Kelso, J. A. S. (2021). Unifying large- and small-scale theories of coordination. *Entropy*, *23*(5), 537.

Kelso, J. A. S., Tognoli, E., Dumas, G. (2014). Coordination dynamics: Bidirectional coupling between humans, machines and brains. In *Presented at the 2014 IEEE International Conference on Systems, Man & Cybernetics* (pp. 2240–2243). IEEE.

Latour, B. (1996). On actor-network theory: A few clarifications. *Soziale Welt*, *47 No*(4), 369–381.

Lesne, A. (2013). Multiscale Analysis of Biological Systems. *Acta Biotheoretica*, *61 No*(1), 3–19.

Longino, H. E. (2020). Interaction: A case for ontological pluralism. *Interdisciplinary Science Reviews: ISR*, *45 No*(3), 432–445.

Longino, H. E. (2021). Scaling up; scaling down: What's missing? *Synthese*, *198*(4), 2849–2863.

Lyon, P. (2006). The biogenic approach to cognition. *Cognitive Processing*, *7 No*(1), 11–29.

Lyon, P., Keijzer, F., Arendt, D., & Levin, M. (2021). Reframing cognition: Getting down to biological basics. *Philosophical Transactions of the Royal Society of London Series B Biological Sciences*, *376 No*(1820), 20190750.

Malafouris, L. (2013). *How things shape the mind: A theory of material engagement*. MIT Press.

Matsuda, Y., Ikeda, K., Ikura, Y., Nishimori, H., & Suematsu, N. J. (2019). Dynamical Quorum sensing in non-living active matter. *Journal of the Physical Society of Japan*, *Vol. 88 No*(9), 093002. The Physical Society of Japan.

McGann, M. (2020). Convergently emergent: Ecological and enactive approaches to the texture of agency. *Frontiers in Psychology*, *11*, 1982.

McGivern, P. (2020). Active materials: Minimal models of cognition? *Adaptive Behavior*, *28*(6), 441–451.

Menon, G. I. (2010). Active matter. In J. M. Krishnan, A. P. Deshpande, & P. B. S. Kumar (Eds.), *Rheology of complex fluids* (pp. 193–218). Springer New York.

Meredith, C., Castonguay, A., Chiu, Y. J., Brooks, A. M., Moerman, P., Torab, P., Wong, P. K. (2021). *Chemical Design of Self-Propelled Janus Droplets*, available at: https://chemrxiv.org/articles/preprint/Chemical_Design_of_Self-Propelled_Janus_Droplets/14378780/1 (accessed 23 April 2021).

Meyer, R. (2020). The nonmechanistic option: Defending dynamical explanation. *The British Journal for the Philosophy of Science*, *71*(3), 959–985.

Müller, V., Sänger, J., & Lindenberger, U. (2013). Intra- and inter-brain synchronization during musical improvisation on the guitar. *PloS One*, *8 No*(9), e73852.

Nordham, C. A., Tognoli, E., Fuchs, A., & Kelso, J. A. S. (2018). How interpersonal coordination affects individual behavior (and Vice Versa): Experimental analysis and adaptive HKB model of social memory. *Ecological Psychology: A Publication of the International Society for Ecological Psychology*, *30 No*(3), 224–249.

Ouellette, N. T., & Gordon, D. M. (2021). Goals and Limitations of modeling collective behavior in Biological Systems. *Frontiers in Physics*, *9*, 341.

Paolo, E. A. D., Di Paolo, E. A., Rohde, M., & De Jaegher, H. (2010). Horizons for the enactive mind: values, social interaction, and play. In J. Stewart, O. Gapenne, and E. A. Di Paolo (Eds.), *Enaction: Toward a new paradigm for cognitive science*. MIT Press.

Paolo, E. D., Buhrmann, T., & Barandiaran, X. (2017). *Sensorimotor life: An enactive proposal*. Oxford University Press.

Ramaswamy, S. (2017). "Active matter", *Journal of Statistical Mechanics: Theory and Experiment*, Vol. 2017 No. 5, p. 054002.

Reynolds, C. W. (1987). Flocks, herds and schools: A distributed behavioral model. In *ACM Siggraph Computer Graphics, 21*(4), 25–34.

Satne, G. (2021). Understanding others by doing things together: An enactive account. *Synthese, 198*(1), 507–528.

Schaller, V., Weber, C., Semmrich, C., Frey, E., & Bausch, A. R. (2010). Polar patterns of driven filaments. *Nature*, *467 No*(7311), 73–77.

Schweitzer, F. (2003). Complex systems and agent models. In *Brownian agents and active particles: Collective dynamics in the natural and social sciences* (pp. 1–49). Springer Berlin Heidelberg.

Seibt, J. (2009). Forms of emergent interaction in general process theory. *Synthese*, *166*(3), 479–512.

Sinhuber, M., van der Vaart, K., Feng, Y., Reynolds, A. M., & Ouellette, N. T. (2021). An equation of state for insect swarms. *Scientific Reports*, *11 No*(1), 3773.

Takatori, S. C., & Brady, J. F. (2015). Towards a thermodynamics of active matter. *Physical Review E*, *91*(3), 032117. https://doi.org/10.1103/PhysRevE.91.032117.

Thompson, E. (2007). *Mind in life: Biology, phenomenology, and the sciences of mind*. Belknap Press of Harvard University Press.

Thutupalli, S., Geyer, D., Singh, R., Adhikari, R., & Stone, H. A. (2018). Flow-induced phase separation of active particles is controlled by boundary conditions. *Proceedings of the National Academy of Sciences of the United States of America*, *115 No*, 5403–5408.

Varela, F., Thompson, E., & Rosch, E. (1991). *The embodied mind: Cognitive Science and Human Experience*. MIT Press.

Varga, S. (2016). Interaction and extended cognition. *Synthese, 193*(8), 2469–2496.

Velasco, A. C., Abkenar, M., Gompper, G., & Auth, T. (2018). Collective behavior of self-propelled rods with quorum sensing. *Physical Review E*, *98*(2), 022605.

Vicsek, T., Czirók, A., Ben-Jacob, E., Cohen, I., & Shochet, O. (1995). Novel type of phase transition in a system of self-driven particles. *Physical Review Letters*, *75 No*(6), 1226–1229.

Zhang, M., Kelso, J. A. S., & Tognoli, E. (2018). Critical diversity: Divided or united states of social coordination. *PloS One*, *13 No*(4), e0193843.