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Opinion

On the Self-Organizing Origins of Agency

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The question of agency and directedness in living systems has puzzled philosophers and scientists for centuries. What principles and mechanisms underlie the emergence of agency? Analysis and dynamical modeling of experiments on human infants suggest that the birth of agency is due to a eureka-like, pattern-forming phase transition in which the infant suddenly realizes it can make things happen in the world. The main mechanism 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. The baby discovers itself as a causal agent. Some implications of this theory are discussed.

Trends

Over the past 30 years, higher-order principles of self-organizing dynamical systems have influenced our understanding of brain, cognition, and behavior.

They might also offer insights into age-old puzzles about the origins of agency and directedness in living things.

Experiments and observations of human infants combined with theoretical modeling suggest that the birth of agency corresponds to a eureka-like phase transition in a coupled dynamical system whose key variables span the interaction between the baby and its environment.

Analysis shows that the main mechanism underlying the emergence of agency is autocatalytic and 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. The prelinguistic baby realizes it can make things happen!

What Is this 'I'?

We humans tend to believe that we are agents, masters and mistresses of our fate, that our deeds and desires are our destiny. Yet, despite a sizeable literature on 'the sense of agency' and its behavioral and neuroimaging correlates (see [1,2] for recent reviews), the scientific basis of causal agency and how we come to experience ourselves as agents is lacking. Agency means action towards an end. When it comes to the behavior of living things, our inability to understand end-directedness forces us to posit (often implicitly) an intelligent agent residing somewhere inside the system that is responsible for the end-directed behavior we observe. The self as a causal agent remains a ghost in the machine awaiting exorcism, perhaps by new insights from the brain and cognitive sciences.

Charles Darwin, in *On the Origin of Species*, touched only briefly on the topic of agency, although he noted how 'admirably adapted' was the woodpecker to catch insects under the bark of trees and how mistletoe 'absolutely' required the agency of certain insects to bring pollen from one flower to another ([3] p.12). His later work on the habits of worms notwithstanding [4], Darwin admitted 'I must promise that I have nothing to do with the origin of the primary mental powers, any more than I have with life itself' ([3] p.189). In the introduction to his remarkable history of physiological psychology, Franklin Fearing [5] noted that 'Even before man speculated about the nature and source of his own experiences, he was probably curious about the agencies by which animal motion was effected' ([5] p.1). Life and motion, Fearing remarks, are almost synonymous terms.

In his famous book *What Is Life?*, Erwin Schrödinger [6], one of the chief architects of quantum mechanics and the author of the famous equation that bears his name, proposed an 'order from order' principle as the physical basis of life. Schrödinger speculated that this new kind of order took the form of an aperiodic crystal, later exposed as the beautiful double helical structure of the DNA molecule [7]. Not much more was said about Schrödinger's order from order principle or his call for 'new laws to be expected in the organism' (but see [8,9]). Still less truck was given to the question raised by Schrödinger in the final chapter of his small book. Each of us, says Schrödinger, has the indisputable impression that the sum total of our own experience and

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memory is unitary and distinct from that of any other person. We humans, for example, have no doubt whatsoever that it is us, and us alone, who direct the motions of our own bodies and foresee its effects. *What is this 'I'?* (italics his) Schrödinger asks, like a voice crying out of the wilderness. Here I ask: where do agency and directedness come from? How does the self as a causal agent come about?

In this Opinion, insight into the origin of agency comes from an unusual and largely untapped source: experiments and observations of human babies. Stranger still is their interpretation in light of the principles and mechanisms of the science of coordination, coordination dynamics. Coordination dynamics [10–30] is a theoretical and empirical approach grounded in the concepts of self-organization in physics, chemistry, and biology and the mathematical tools of nonlinear dynamical systems [31–33]. A distinguishing aspect of coordination dynamics is that it is tailored specifically to handle the activities of animate, living things. The aim is to understand how functionally significant patterns of coordinated behavior emerge, persist, adapt, and change in a variety of different systems at multiple levels of description, from cells and their circuitry to brains and people. The behavioral, cognitive, and social processes studied in coordination dynamics include moving, perceiving, feeling, thinking, deciding, learning, remembering, developing, aging, and so on [10–30,34–38].

A main aspect of self-organizing dynamical systems [17] 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. Self-organizing systems are, it seems, selfless. They do not contain meaning or aspects that one would associate with meaning, such as agency, intention, will, or purpose. They can appear to be goal or end directed, but they are not organized around goals [39]. In fact, any hint of 'self' or agency is banished in physically based theories of self-organization [31,32,40]. Self-organization means that the system organizes itself, not that there is a self doing the organizing. So where does the self as a causal agent come from?

In an earlier work, I proposed that self-organizing processes in living things must (somehow) give rise to agency; that the most fundamental kind of consciousness, the awareness of self, must spring (somehow) from the ground of spontaneous self-organized activity [41,42]. We come into the world moving. We are never still. It is well known that the elementary spontaneous movements we are born with, whether we view them in terms of elementary reflexes or pattern generators, consist of a large repertoire of spontaneous movements, making a fist, kicking, sucking, and so forth. Coordination dynamics refers to the patterns that the system is capable of producing spontaneously at a given point in time along with the attractor landscape that defines the relative stability of these patterns as intrinsic dynamics [13]. Intrinsic dynamics is important to know because it influences what can be changed or modified by new experiences and how such change occurs (e.g., whether change is smooth or abrupt) [43,44]. The eminent philosopher and evolutionary biologist, Maxine Sheets-Johnstone, has repeatedly pointed to, and provided evidence for, the primacy of movement as 'the mother of all cognition', presaging every conscious mind that ever said 'I'. 'Spontaneous movement' argues Sheets-Johnstone [45] 'is the constitutive source of agency, of subjecthood, of selfhood, the dynamic core of ourselves as agents, subjects, selves'. In her elegantly chosen phrase, 'Movement forms the I that moves before the I that moves forms movement' ([45] p. 119). For Sheets-Johnstone, then, spontaneous movements and the kinesthetic feelings that accompany them are the foundation of first-person experience of agency.

So is this all there is to it? A critic might inquire by what mechanism something as meaningful as causal agency arises out of the (apparently meaningless) movements we are born with? How does our awareness of agency emerge from the electrical and chemical activity of the brain? Or does understanding agency rather require a broader view that encompasses brain, body, and environment, as theories of radical embodiment would demand [34,46–48]. The present Opinion, implemented in a specific theoretical model [49], addresses these and related queries. It builds, like all scientific research, on earlier ideas but says that agency arises when spontaneous activity is coupled to the world, forming a coordinative structure [50–53]. Coordinative structures are functional linkages among component parts and processes that are temporarily constrained to act as a single coherent unit. They are not hard-wired and fixed in the way we tend to think of neural circuits; they are context dependent and are best understood, like the emergence of life itself [9], in terms of coupled dynamical systems (see also [54]). A strong case can be made that coordinative structures, also known as functional synergies [55] or synergies of meaningful movement [45], are units of selection in evolution [56,57] and intentional change [58,59]. The ability of complex systems to softly assemble themselves into functional synergies or coordinative structures in a context-sensitive fashion offers significant selectional advantages. Coordinative structures are embodiments of the principle of functional equivalence [60]: they handle the tremendous degeneracy of living things, using different combinations of elements and recruiting new pathways 'on the fly' to produce the same outcome [61–63].

My opinion is that a coordinative structure 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, 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 and its environment. The idea is that, when the baby realizes it is causing the world to change, it experiences itself as an agent for the very first time. This igniting of agency has a eureka-like, 'aha' effect; mathematically, it corresponds to a bifurcation in a coupled dynamical system. 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 [10,12–14,31,32,53,60,64]. 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 [65] and of the feedforward network motifs so ubiquitous in the design of biological circuits [66]. 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 [67–73]), a synergetic phase transition, gives rise to self (Box 1). The root soil of agency, as Sheets-Johnstone [45] would say, rests on primal animation, on being alive and moving. In addition, its first expression takes the form of a phase transition, the most fundamental signature of self-organization in natural systems.

Experiment Crucis…Or Is it?

At 2 months and 27 days, Laurent was surprised and frightened by the first shake of the rattle which was unexpected. On the other hand, since the second or third shake, he swung his right arm (connected to the rattle) with regularity, whereas the left remained almost motionless. Now the right could easily move freely without moving the rattle, the string being loose enough to permit Laurent to suck his thumb, for instance without pulling at the balls. **It therefore seems that the swinging was intentional...Conscious coordination seems definite** [my bold] Jean Piaget, 1952 ([74] p. 161)

Piaget's observations of his baby son Laurent appear in a translation of his book, *The Origins of Intelligence in Children* first published in French in 1936. Thirty years or so later, American psychology took up the same problem in the context of Skinnerian conditioning and called it 'mobile conjugate reinforcement', MCR for short. The many scientists who have employed the

Box 1. Neural Mechanisms for the Emergence of Agency

A natural question to ask is what is going on in the baby's head when the baby discovers he/she is a causal agent and is making the mobile move. Much interest has been directed toward identifying how the different components of self-consciousness are integrated to achieve a conscious experience of oneself, a unitary entity 'I'. By far the greatest emphasis is on where this is achieved. The feeling of owning a body part and where the body is located in space (so-called 'self-location') has been tied to the posterior cingulate cortex, an integrative area that links signals about body ownership (e.g., ventral premotor and parietal regions) and self-location (e.g., hippocampus, intraparietal sulcus) [97,98].

But how does conscious coordination, in Piaget's words, become definite? Is the neural correlate of the pattern forming eureka effect a phase transition in the baby's brain? Or is the nervous system, at least in the case of human infants, better viewed as a necessary medium for agency to arise? The origin of agency is understood here as a self-organizing pattern-formation process. Sensorimotor phase transitions have been observed in adult brain studies using EEG, MEG, and fMRI. Is the emergence of agency accompanied by a sensorimotor phase transition in the baby's brain? Such critical phenomena are ubiquitous in both the nervous system and behavior [67–73,99] and attest to the significance of collective behavior in coordinating large numbers of neurons. Phase transitions are the simplest expression of self-organization in the human brain [9,13,14,53,60]. More and more evidence is accruing that the brain is a veritable geography of improvised rhythms [100–104] that are coupled together in various, often subtle ways for particular functions. Over the past 20 years, it has become apparent that neural synchrony is only one manifestation of the brain's self-organizing coordination dynamics. Far more variable, plastic, and fluid forms of coordination exist, in which tendencies for component parts to come together coexist with tendencies for the same parts to behave as autonomous units [13,30,105–107]. Such metastable coordination dynamics is characteristic of systems like brains and bodies composed, as they are, of parts that are heterogeneous. In all likelihood, once formed, the interaction between baby and mobile is metastable, indicative of relative not pure absolute coordination or synchrony [13,81].

MCR and related paradigms ever since, have used it as a way to study something else (learning, memory, cognitive, and motor development, etc.), certainly not as a clue to the origin of self as a causal agent. What may have been missed, in my opinion, is the essence of what it means to be aware of oneself as a source of control, of doing something deliberately, and how that comes about.

The prime mover in the so-called MCR paradigm was the late Carolyn Rovee and her colleagues ([75–77] see also [49] for review). Just as Piaget had done 30 years earlier (although strangely his observations are not mentioned), Rovee and Rovee [75] tied a ribbon to the ankles of 3–4-month-old babies and attached it to a mobile hanging over the baby's crib. Conjugate reinforcement refers to the fact that any foot or leg movements caused the mobile to move, creating sights, sounds, and feelings that babies seem to enjoy. Remarkably, in the first few minutes of such 'conjugate reinforcement', the baby's kicking rate tripled or quadrupled relative to control infants who were presented with identical but noncontingent auditory, visual and kinesthetic stimulation (Figure 1).

It seems pretty obvious that babies like making the mobile produce movements and sounds, of effecting a happening in the world. But what actually is behind all this? If as Piaget says, 'conscious coordination seems definite' how are we to understand how such consciousness arises? Where does the conscious agent come from? To answer these questions, we need to take a closer look at the baby–mobile interaction through the eyes of the coordination dynamics of moving bodies. To do that requires a careful examination of the MCR phenomenon, which has been reproduced and refined in many experiments (see reviews in [49,76,77]).

What's Missing?

If the unified experience that constitutes awareness of self as causal agent is really the formation of a coordinative structure, this means that the baby is always coupled to the world. For the late developmental psychologist, Eleanor Gibson, the relation between organism and environment is one of reciprocity. The dimensions and properties of the environment constrain the actions that can be performed, and the actions that an organism performs on objects and surfaces produce changes in the environment [78]. (A more modern and technical version of this idea is the free

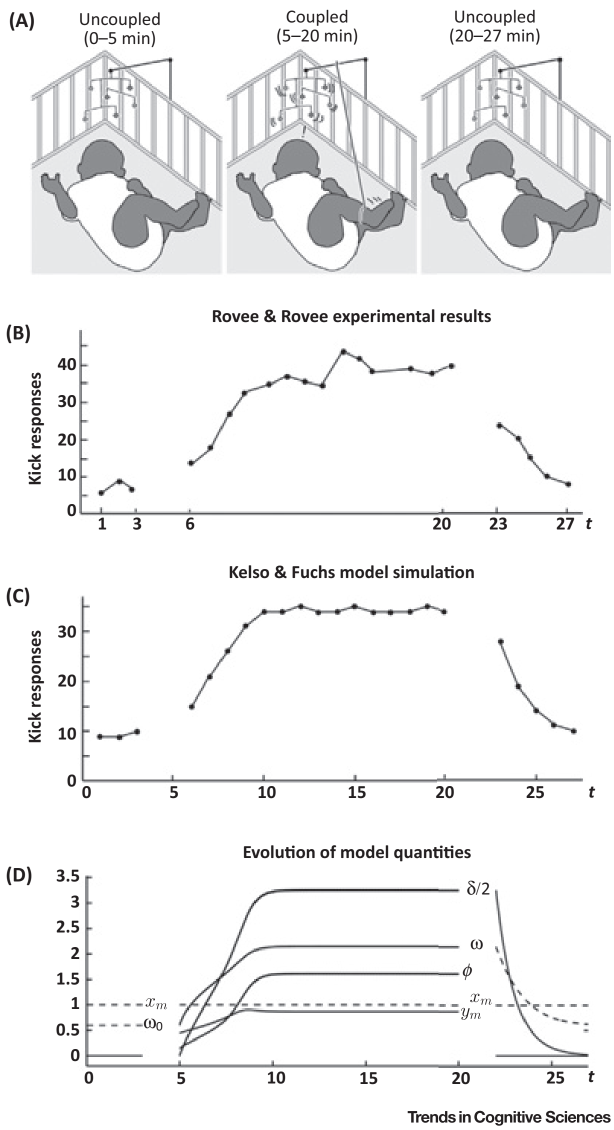

Figure 1. **The Baby–Mobile Experiment: Data and Theoretical Model**. (A) The three phases of the MCR paradigm. (B,C) Comparison of experimental findings (B) and model (C). (D) Evolution of model quantities over time during a single trial run. On the left part, as in (A), the baby and mobile are uncoupled. The mobile is still and the baby exhibits a spontaneous kicking rate ω_0 with amplitude x_m. At around $t = 5$, the baby and the mobile are coupled. Baby's kick rate, ω and amplitude of mobile movement y_m rapidly increase up to a steady state as does the parameter δ. Moreover, the phase relation between the baby's leg movement and the motion of the mobile increases to ø = 90 degrees, characteristic of a resonant coupled state. At $t = 20$, the baby and the mobile are again uncoupled; δ and kick rate decay back to a baseline level. Notice in both data and model that, after the baby is decoupled from the mobile, it does not simply stop moving (i.e., leg movements continue but at a steadily decreasing rate).

energy principle [79], in which perception is an inevitable consequence of active exchange with the environment.) To come to grips with agency as a coupled dynamical system at the very least requires measures of the baby's movements, the motion of the mobile, and the coordinative relation between the two. (Coordination dynamics refers to the latter as collective variables and seeks to identify the collective variable dynamics on a given level of description [13,17–20].) In the style of classical behaviorism, the early work of Rovee-Collier and others measured only response rate: an observer records the number of kicks in a given period of time. Later work is more sophisticated providing, for example, detailed kinematic measures of the baby's hip, knee, and ankle displacements (see [49] for review). However, to my knowledge, not a single study has recorded the motion of the mobile, thereby obviating the possibility of obtaining any information about its relation to the baby's movements. If, as proposed here, the dawn of agency breaks when the infant discovers its spontaneous movements are causing the world to change and if that process is to be understood in terms of self-organizing coordination dynamics, then measures of the coordinative relation between the baby's end effector and the mobile are crucial. But in most studies of MCR, the mobile and the way it moves are relegated to the status of a mere stimulus and, hence, are ignored. Likewise, although researchers appreciate that it is through the coupling between intrinsic (self-generated) and extrinsic inputs that infants discover adaptive solutions to task situations [80], the coupling itself is never quantified. Hip–knee coordination may be measured but not the temporal relationship between mobile and kicking movement, itself a compressed reflection of the visual-auditory-kinetic-kinesthetic linkage [81]. Faced with these shortcomings, for now the only solution is to assume that such measures can be made and proceed to a theoretical model that reproduces the extant data and predicts a number of novel effects (see [49]). The intent of such analysis is to reveal the basic mechanism of the emergence of agency, how 'I' emerges as a result of bidirectional information exchange between the baby and its world.

The Model

Simply stated, the model is a dynamical system consisting of three equations, one for the baby's leg movements, one for the jiggling motion of the mobile, and one for the functional coupling between the two (see [49] for empirical justification and mathematical details). Briefly, it makes sense to model the back and forth movements of the baby's leg as a limit cycle oscillator. Stable limit cycles correspond to closed orbits in phase space that attract nearby trajectories on the in- and outside. Thus, if the movement trajectory is perturbed or subject, as all movements are, to natural variation, it returns to its original orbit. This is precisely what happens in detailed studies of rhythmic movements in humans (including babies) and it is one reason why limit cycles have been used so extensively over the past decades in neural and behavioral models of human and animal movements as well as in robotics applications ([82,83] for recent reviews).

The mobile is a complex stimulus whose motion is attractive to the baby and becomes more so when the baby moves it. Without any baby kicks, the simplest model for the mobile is that of a damped oscillator (see [84] for a similar kind of approach). Nudge the mobile and it will oscillate back and forth depending on its damping. But the damping has to be just right. If it is too small, the baby can simply kick once and then just watch and listen. However, that is not what actually happens. All the studies on mobile conjugate reinforcement emphasize that infants suddenly increase their kick frequency to keep the mobile moving. The faster the babies kick, the more the mobile moves, and the more noise it makes the more the babies kick. In the model, this change in the kick frequency is realized by an increase in the force driving the baby's leg movement (the parameter δ in the limit cycle model) coupled to the mobile oscillator y with a dynamics described by $\dot{\delta} = ay^2 - \kappa\delta$. For reasons of space, this is the only equation I shall discuss since it is at the core of the pattern-forming transition that is deemed to underlie causal agency. The interpretation of a and κ are straightforward. Much evidence indicates that high arousal and sustained visual attention (often accompanied by open arm and leg movements, and neurobiologically by cholinergic agonists [85]) are typical of 9–12-week-old infants [86]. In the model, the parameter a reflects the tight linkage between the salient auditory and visual features of the mobile, the kinesthetic information generated by vigorous leg movements, and the haptic information that arises as a result of the baby's foot being tethered to the mobile. If a is too low, the driving force δ is small and the baby's kick rate does not increase much. Only if a reaches a critical value does δ start to increase. A positive feedback loop is triggered. The increase in δ causes kicking rate to increase. Faster kicks feed into the mobile y and its rate also increases. This leads to an even larger value of y because the mobile gets closer to resonance, which increases δ even further. The frequency of leg movement, the amplitude of mobile movement, and the value of δ saturate when the baby–mobile system is close to resonance. In the face of such excitation, κ is the inhibiting factor that limits the increase in δ. One can see this from the equation: the bigger the value of δ, the more important the decay term $\kappa\delta$ becomes until a steady state is reached. For a given trial run, the baby is kicking as much as she is going to kick. The frequencies and amplitudes of the mobile and leg movements reach a plateau and are pretty stationary, as is the value of δ. κ limits the kick rate and determines how it decays when the mobile and the baby are decoupled. The basic story is displayed in Figure 1, which shows the MCR paradigm (Figure 1A), the original Rovee and Rovee data (Figure 1B), the model simulation (Figure 1C) and the flow of the dynamics of the parameters and variables of the model (Figure 1D) over a single trial of the experiment.

The intent here is not to go into the mathematical details of the model and its specific predictions, which are available elsewhere [49]. Rather it is to suggest, as a result of the mapping between data and model, that the transition from an uncoupled state to a persistent coupled state, from spontaneous movement to deliberate action, is the root of agency. A spontaneous kick moves the mobile and moving the mobile leads to more forceful kicks, in Carolyn Rovee's words 'effectively more intense responding produced a more intense reward' ([75] p. 35). Outside this response-for-reward framework, the main point is that when the value of a single parameter *a* reaches a critical point, it gives rise to the 'eureka effect', a sense of causal agency, 'this is me making things happen in the world not some outside force making that attractive mobile oscillate'. The kicking rate increase is an autocatalytic or positive feedback process, typical of many pattern-forming systems in nature [31,65,66]. As Buhrman and Di Paolo intuit in their philosophical writings 'the sense of oneself. . .corresponds to what we experience during the ongoing adventure of establishing, losing and re-restablishing meaningful interactions with the world' [46]. Sheets-Johnstone [87], drawing on our specific formulation, says it even better: for her, the infant kicking in Phase 1 of the experiment accords with an elementary form of spontaneity, the infant is simply alive in its primal animation. In Phase 2, the infant realizes a relationship exists between what it is doing and the fact that the mobile moves above its head. This realization of an 'I do' is essentially the realization of an if–then relationship: if I kick my legs, then the mobile moves. The transition to 'I can', the 'eureka' moment, the realization of agency, follows naturally: 'I can make the mobile move', 'I can make something happen'. For Sheets-Johnstone, this moment is validated by Phase 3, the phase in which the infant stops kicking and when the infant realizes it is no longer an agent and the normal flow from intention to effect is broken (see also [88]). The model demonstrates mathematically what this three-tiered, experiential account of the emergence of agency entails (see also Outstanding Questions).

Concluding Remarks

Mundane as a baby's 'kicks' may be, they, along with the movement of the mobile they cause, hide a profound feature of the world and our place in it. The pairing of movement and motion, motor and sensory, action and perception, matter and mind, typically treated as separate, becomes a meaningful unified experience. Awareness of their intimate relation is the basis of conscious agency. The infant agent is not just an entity that does things [89] or senses that something is happening to it [90]. Rather, the essence of agency is appreciation of the fact that this is not some outside force moving the mobile, this is me. The baby is now in charge, so to speak, of its own destiny. From here on in, the baby is an agent: it knows it can make things happen and it develops expectations on that basis (Box 2).

Just as two cells exchange matter through the joint action of stimulants and inhibitors to form simple biological structures, so the baby and the mobile exchange information to form a coupled dynamical system. It is the transition from being uncoupled with the world to being coupled to it that creates meaning, the 'aha' effect announcing the origins of agency. Excitatory drive of the baby's leg movements (underpinned in all likelihood by the action of neuromodulators) creates a resonant state with the environment that is inhibited only by that fact that it is not physically possible or energetically economical to go beyond that (the κ parameter).

The fact that the baby keeps kicking after the coupling is removed suggests that predictive mechanisms are formed as a result of the coupling between baby and mobile. Such a 'corollary discharge' has been proposed as a means by which the organism distinguishes movements of

Outstanding Questions

Coordination dynamics predicts quantitative effects, such as critical fluctuations and critical slowing down, as coordinated states form and change. Can these be detected in the baby–mobile and related paradigms?

Does the loss or absence of agency, implicated in several brain disorders and mental health problems, also take the form of a dynamic instability or phase transition?

Evidence suggests that the brain produces actions in terms of internal signals that specify their expected sensory consequences. Is such predictive corollary discharge along with memory for feelings of movement (kinesthesis) still intact in minimally conscious patients? Does it underlie their awareness that they can make things happen?

If the Kelso-Fuchs model can be implemented in a robot, does this mean that the robot can be said to possess agency? In the present theory, agency arises as a phase transition in the coordination dynamics and phase transitions underlie the 'eureka' experience. Thus, the present theory embraces both objective (3rd person) and subjective (1st person) descriptions. Robots may emulate the former and mimic the latter. But agency depends on being alive and on being a differentiated self. Robots and machines are not alive and do not have 1st person experiences.

In coordination dynamics, collective variables, by definition, are low-dimensional descriptions of complex systems. They are meaningful and relational and relatively independent of the component parts and processes of which they are constituted. Arbitrary divisions between sensory and motor, stimuli and responses, perception and action, and so on, disappear in the face of the fact that they always exist inside a coordination. Is it, then, not so much a matter of carving 'as a bad carver might' (Socrates' Phaedrus 265E), as of failing to see complementarities? The identification of collective variables and their dynamics in studies of infant cognitive development is a key step in moving dynamical approaches beyond metaphor.

Box 2. How Early Does Agency Arise?

It seems likely that agency emerges even earlier than 3 months. One might argue generally that the human is a self-organizing system from the moment of conception, through embryogenesis, the post-natal period onward to the infant stage, and beyond. My interest, however, just as in early quantitative studies of movement coordination [10,12–14], is in establishing empirically and theoretically whether the concept of self-organization is even relevant to agency or end-directedness and, if it is, to identify the self-organizing dynamics in a concrete situation [13,19,60]. Certainly, early studies [108] showed that 2-day-old infants (in a state of 'quiet alertness') engage in more frequent sucking bursts to their own mother's voice reading Dr Seuss's 'To think that I saw it on Mulberry Street' over that of another female. A main focus of such research is to investigate how effective the fetal auditory system is in detecting and responding to the maternal spoken voice. Evidence of differential sensitivity to the mother's voice occurs very early in life, even prenatally [109]. What is less emphasized (and again not measured) is that the infant's sucking produces the mother's voice and, as in the baby–mobile case, the mother's voice causes the baby to suck more. Two-day-old infants, in fact, do work to produce their mother's voices in preference to other mother's voices or acoustic stimuli. Whereas the neonate's preference for the mother's voice suggests a role in infant bonding, these data are also highly consistent with the theory here, namely that the basis of agency is making something happen in the world. And making some things happen is more important than others.

It should be emphasized that MCR is not some isolated phenomenon. For example, studies of non-nutritive sucking show that 2-month-old babies couple best to a contiguous (time-varying) sound that varies directly with the amount of pressure applied to the pacifier [110]. To their credit, the authors view their results as a 'transition toward systematic self-exploration [that] is linked to the development of a new sense of self in infancy' ([110] p.216). However, no measures of auditory–movement coupling were obtained, which would enable an interpretation of agency's origins in terms of coordination dynamics.

the environment that are consequences of its own motion, from environmentally produced motions [91–95]. Sperry's insightful remarks that '. . .the experience of the organism is integrated, organized and has its meaning in terms of coordinated movement' ([96] p. 295) is as good a way as any to express the emergence of self as a causal agent. As shown here, the concepts, methods, and tools of self-organizing coordination dynamics put clothes on Sperry's words.

In short, it does not seem too far of a stretch of the imagination to propose that evolutionarily constrained processes of self-organization (real organisms coupled to real environments living in the metastable regime of their coordination dynamics) are at the origins of (meaningful) information and agency itself. This step may signal an end to false contrasts about whether coordination in living things is a directed or self-organized process and point rather to their inherently complementary and unified nature. In answer to Schrödinger's questions raised at the beginning, the causal influence that the baby exerts on its world is the source of what we call 'I' and his 'new laws to be expected in the organism' are the laws of self-organizing coordination dynamics and their mechanistic realization.

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References

1. Chambon, V. *et al.* (2014) From action intentions to action effects: how does the sense of agency come about? *Front. Human Neurosci.* 8, 320
2. Swiney, L. and Sousa, P. (2014) A new comparator account of auditory hallucinations: how motor prediction can plausibly contribute to the sense of agency for inner speech. *Front. Human Neurosci.* 8, 675
3. Darwin, C.R. (1859) *On the Origin of Species,* John Murray
4. Darwin, C.R. (1881) *The Formation of Vegetable Mould, through the Action of Worms, with Observations on their Habits,* John Murray
5. Fearing, F. (1970) *Reflex Action: A Study on the History of Physiological Psychology,* MIT Press 1930
6. Schrödinger, E. (1944) *What is Life?* Cambridge University Press
7. Watson, J.D. and Crick, F.H.C. (1953) A structure for deoxyribose nucleic acid. *Nature* 171, 737–738

8. Kelso, J.A.S. and Haken, H. (1995) New laws to be expected in the organism: synergetics of brain and behavior. In *What Is Life? The Next 50 Years* (Murphy, M. and O'Neill, L., eds), pp. 137–160, Cambridge University Press
9. Friston, K.J. (2013) Life as we know it. *J. R. Soc. Interface* 10, 20130475
10. Kelso, J.A.S. (1984) Phase transitions and critical behavior in human bimanual coordination. *Am. J. Physiol.* 15, R1000–R1004
11. Turvey, M.T. (1990) Coordination. *Am. Psychologist* 45, 938–953
12. Haken, H. *et al.* (1985) A theoretical model of phase transitions in human hand movements. *Biol. Cybern.* 51, 347–356
13. Kelso, J.A.S. (1995) *Dynamic Patterns: The Self-Organization of Brain and Behavior,* MIT Press
14. Schöner, G. and Kelso, J.A.S. (1988) Dynamic pattern generation in behavioral and neural systems. *Science* 239, 1513–1520
15. Fuchs, A. and Jirsa, V.K., eds (2008) *Coordination: Neural, Behavioral and Social Dynamics*, Springer
16. Jirsa, V.K. and Kelso, J.A.S., eds (2004) *Coordination Dynamics: Issues and Trends*, Springer
17. Kelso, J.A.S. (2001) Self-organizing dynamical systems. In *International Encyclopaedia of Social and Behavioral Sciences* (Smelser, N.J. and Baltes, P.B., eds), pp. 13844–13850, Pergamon
18. Oullier, O. and Kelso, J.A.S. (2009) Social coordination from the perspective of coordination dynamics. In *Encyclopedia of Complexity and Systems Science* (Meyers, R.A., ed.), pp. 8198–8212, Springer
19. Kelso, J.A.S. (2009) Coordination dynamics. In *Encyclopedia of Complexity and System Science* (Meyers, R.A., ed.), pp. 1537–1564, Springer
20. Kelso, J.A.S. *et al.* (2013) Outline of a general theory of behavior and brain coordination. *Neural Netw.* 37, 120–131
21. Lagarde, J. (2013) Challenges for the understanding of social coordination. *Front. Neurobot.* 7, 1–9
22. Beek, P.J. *et al.* (1995) Dynamical models of movement coordination. *Hum. Movement Sci.* 14, 573–608 http://dx.doi.org/10.1016/0167-9457(95)00028-5
23. Turvey, M.T. and Carello, C. (2012) On intelligence from first principles: guidelines for inquiry into the hypothesis of physical intelligence. *Ecol. Psychol.* 24, 3–32
24. Van Orden, G. *et al.* (2003) Self-organization of cognitive performance. *J. Exp. Psychol. Gen.* 132, 331–351
25. Warren, W.H. (2006) The dynamics of perception and action. *Psychol. Rev.* 113, 358–389
26. Dumas, G. *et al.* (2014) The human dynamic clamp as a paradigm for social interaction. *Proc. Natl. Acad. Sci.* 111, E3726–E3734
27. Jantzen, K.J. *et al.* (2009) Coordination dynamics of large-scale neural circuitry underlying sensorimotor behavior. *J. Cogn. Neurosci.* 21, 2420–2433 http://dx.doi.org/10.1162/jocn.2008.21182
28. Huys, R. *et al.* (2014) Functional architectures and structured flows on manifolds: a dynamical framework for motor behavior. *Psychol. Rev.* 121, 302–336
29. Tognoli, E. and Kelso, J.A.S. (2009) Brain coordination dynamics: true and false faces of phase synchrony and metastability. *Prog. Neurobiol.* 87, 31–40 http://dx.doi.org/10.1016/j.pneurobio.2008.09.014
30. Bressler, S.L. and Kelso, J.A.S. (2001) Cortical coordination dynamics and cognition. *Trends Cogn. Sci.* 5, 26–36
31. Haken, H. (1977) *Synergetics, An Introduction: Non-Equilibrium Phase Transitions and Self-Organization in Physics, Chemistry and Biology,* Springer
32. Nicolis, G. and Prigogine, I. (1977) *Self-Organization in Nonequilibrium Systems,* Wiley
33. Eigen, M. (2013) *From Strange Simplicity to Complex Familiarity,* Oxford University press
34. Chemero, A. (2001) Dynamical explanation and mental representations. *Trends Cogn. Sci.* 5, 141–142
35. Thelen, E. and Smith, L. (1994) *A Dynamic Systems Approach to the Development of Cognition and Action,* MIT Press
36. Oullier, O. *et al.* (2008) Social coordination dynamics: measuring human bonding. *Soc. Neurosci.* 3, 178–192 http://dx.doi.org/10.1080/17470910701563392
37. Riley, M.A. *et al.* (2011) Interpersonal synergies. *Front. Psychol.* 2, 38 http://dx.doi.org/10.3389/fpsyg.2011.00038
38. Tschacher, W.W. and Dauwalder, J.P., eds (2003) *The Dynamical Systems Approach to Cognition: Concepts and Empirical Paradigms Based on Self-Organization, Embodiment and Coordination Dynamics*, World Scientific
39. Kondepundi, D. *et al.* (2015) End-directed evolution and the emergence of energy-seeking behavior in a complex system. *Phys. Rev. E* 91, 050902
40. Laughlin, R.B. and Pines, D. (2000) The theory of everything. *Proc. Natl. Acad. Sci.* 97, 28–31
41. Kelso, J.A.S. (2002) The complementary nature of coordination dynamics: self-organization and the origins of agency. *J. Nonl. Phen. Compl. Sys.* 5, 364–371
42. Kelso, J.A.S. and Engstrøm, D.A. (2006) *The Complementary Nature,* MIT Press
43. Kelso, J.A.S. *et al.* (1987) Phase-locked modes, phase transitions and component oscillators in coordinated biological motion. *Phys. Scr.* 35, 79–87
44. Kostrubiec, V. *et al.* (2012) Beyond the blank slate: routes to learning new coordination patterns depend on the intrinsic dynamics of the learner–experimental evidence and theoretical model. *Front. Hum. Neurosci.* 6, 212 http://dx.doi.org/10.3389/fnhum.2012.00222
45. Sheets-Johnstone, M.S. (1999) *The Primacy of Movement,* John Benjamins
46. Buhrman, T. and Di Paolo, E. (2015) The sense of agency–a phenomenological consequence of enacting sensorimotor schemes. *Phen. Cogn. Sci.* 1–30 http://dx.doi.org/10.1007/s11097-015-9446-7
47. Noë, A. (2009) *Out of Our Heads,* Hill and Wang
48. Thompson, E. and Varela, F.J. (2001) Radical embodiment: neural dynamics and consciousness. *Trends Cogn. Sci.* 5, 418–425
49. Kelso, J.A.S. and Fuchs, A. (2016) The coordination dynamics of mobile conjugate reinforcement. *Biol. Cybern.* 110, 41–53
50. Kelso, J.A.S. *et al.* (1979) On the nature of human interlimb coordination. *Science* 203, 1029–1031
51. Kugler, P.N. *et al.* (1980) Coordinative structures as dissipative structures I. Theoretical lines of convergence. In *Tutorials in Motor Behavior* (Stelmach, G.E. and Requin, J., eds), pp. 1–40, Amsterdam, North Holland
52. Kelso, J.A.S. *et al.* (1980) Coordinative structures as dissipative structures II. Empirical lines of convergence. In *Tutorials in Motor Behavior* (Stelmach, G.E. and Requin, J., eds), pp. 49–70, Amsterdam, North Holland
53. Kelso, J.A.S. (2014) The dynamic brain in action: coordinative structures, criticality and coordination dynamics. In *Criticality in Neural Systems* (Plenz, D. and Niebur, E., eds), pp. 67–106, Wiley
54. Beer, R. (1995) Dynamical approaches to cognitive science. *Trends Cogn. Sci.* 4, 91–99
55. Kelso, J.A.S. (2009) Synergies: atoms of brain and behavior. *Adv. Exp. Med. Biol.* 629, 83–91
56. Maynard-Smith, J. and Szathmáry, E. (1995) *The Major Transitions in Evolution,* Oxford University Press
57. Corning, P.A. (2012) Rotating the Necker cube: A bioeconomic approach to cooperation and the causal role of synergy in evolution. *J. Bioecon.* 15, 171–193
58. Wilson, D.S. *et al.* (2014) Evolving the future: toward a science of intentional change. *Behav. Brain Sci.* 37, 395–460
59. Kostrubiec, V. and Kelso, J.A.S. (2014) Incorporating coordination dynamics into an evolutionarily grounded science of intentional change. *Behav. Brain Sci.* 37, 428–429
60. Kelso, J.A.S. (2012) Multistability and metastability: understanding dynamic coordination in the brain. *Phil. Trans. R. Soc. B* 367, 906–918

61. Edelman, G.E. and Gally, J. (2001) Degeneracy and complexity in biological systems. *Proc. Nat. Acad. Sci.* 98, 13763–13768
62. Greenspan, R.J. (2012) Biological indeterminacy. *Sci. Eng. Ethics.* 18, 447–452
63. Kelso, J.A.S. and Tuller, B. (1984) A dynamical basis for action systems. In *Handbook of Cognitive Neuroscience* (Gazzaniga, M. S., ed.), pp. 321–356, Plenum
64. Kelso, J.A.S. (2010) Instabilities and phase transitions in human brain and behavior. *Front. Hum. Neurosci.* 4, 23 http://dx.doi.org/10.3389/fnhum.2010.00023
65. Gierer, A. and Meinhardt, H. (1972) A theory of biological pattern formation. *Kybernetik* 12, 30–39
66. Alon, U. (2007) *An Introduction to Systems Biology: Design Principles of Biological Circuits,* Chapman & Hall/CRC
67. Kelso, J.A.S. *et al.* (1992) A phase transition in human brain and behavior. *Phys. Lett. A* 169, 134–144
68. Fuchs, A. *et al.* (1992) Phase transitions in the human brain: spatial mode dynamics. *Int. J. Bifurcat. Chaos* 2, 917–939
69. Jirsa, V.K. *et al.* (1994) A theoretical model of phase transitions in the human brain. *Biol. Cybern.* 71, 27–35
70. Kelso, J.A.S. and Fuchs, A. (1995) Self-organizing dynamics of the human brain: critical instabilities and Sil'nikov chaos. *Chaos* 5, 64–69
71. Meyer-Lindenberg, A. *et al.* (2002) Transition between dynamical states of differing stability in the human brain. *Proc. Natl. Acad. Sci. U. S. A.* 99, 10948–10953
72. Mayville, J.M. *et al.* (1999) Spatiotemporal reorganization of electrical activity in the human brain associated with a phase transition in rhythmic auditory-motor coordination. *Exp. Brain Res.* 127, 371–381
73. Banerjee, A. *et al.* (2008) Mode level cognitive subtraction (MLCS) quantifies spatiotemporal reorganization in large-scale brain topographies. *Neuroimage* 15, 663–674
74. Piaget, J. (1952) *The Origins of Intelligence in Children (trans. Margaret Cook),* International Universities Press
75. Rovee, C.K. and Rovee, D.T. (1969) Conjugate reinforcement of infant exploratory behavior. *J. Exp. Child. Psychol.* 8, 33–39
76. Rovee-Collier, C.K. and Gekoski, M.J. (1979) The economics of infancy: a review of conjugate reinforcement. In *Advances in Child Development and Behavior* (Reese, H.W. and Lipsitt, L.P., eds), pp. 195–255, Academic Press
77. Mullally, S. and Maguire, E. (2014) Learning to remember: the early ontogeny of episodic memory. *Dev. Cogn. Neurosci.* 9, 12–29
78. Gibson, E.J. (1993) Ontogenesis of the perceived self. In *The Perceived Self* (Neisser, U., ed.), pp. 25–42, Cambridge University Press
79. Friston, K. (2010) The free-energy principle: a unified brain theory? *Nat. Rev. Neurosci.* 11, 127–138
80. Angulo-Kinzler, R.M. (2001) Exploration and selection of intralimb coordination patterns in 3-month-old infants. *J. Motor Behav.* 33, 363–376
81. Kelso, J.A.S. *et al.* (1990) Action-perception as a pattern formation process. In *Attention and Performance XIII* (Jeannerod, M., ed.), pp. 139–169, Erlbaum
82. Huys, R. *et al.* (2014) Functional architectures and structured flows on manifolds: a dynamical framework for motor behavior. *Psychol. Rev.* 121, 302–336
83. Ijspeert, A. *et al.* (2013) Dynamical movement primitives: learning attractor models for motor behaviors. *Neural Comput.* 25, 328–373
84. Goldfield, E.C. *et al.* (1993) Infant bouncing: the assembly and tuning of action systems. *Child Dev.* 64, 1128–1142
85. Baurer, M. *et al.* (2012) Cholinergic enhancement of visual attention and neural oscillations in the human brain. *Curr. Biol.* 22, 397–402
86. Lavelli, M. and Fogel, A. (2013) Interdyad differences in early mother-infant face-to-face communication: real-time dynamics and developmental pathways. *Dev. Psychol.* 49, 2257–2271
87. Sheets-Johnstone, M.S. (in press) Agency: phenomenological insights and dynamic complementarities. *Phen. Cogn. Sci.*
88. Haggard, P. (2005) Conscious intention and motor cognition. *Trends Cogn. Sci.* 9, 290–295 http://dx.doi.org/10.1016/j.tics.2005.04.012
89. Wegner, D. (2002) *The Illusion of Conscious Will,* MIT Press
90. Damasio, A. (2010) *Self Comes to Mind,* Pantheon
91. Teuber, H-L. (1966) Summation: Convergences, Divergences, Lacunae. In *Brain and Conscious Experience* (Eccles, J.C., ed.), pp. 575–583, Springer
92. Evarts, E.V. (1971) Feedback and corollary discharge: a merging of concepts. In *Central Control of Movement* (Evarts, E.V. *et al.*, eds), pp. 86–112, MIT Press
93. Kelso, J.A.S. and Wallace, S.A. (1978) Conscious mechanisms in movement. In *Information Processing and Motor Control* (Stelmach, G.E., ed.), pp. 79–116, Academic Press
94. Wolpert, D.M. and Flanagan, J.R. (2009) Forward models. In *The Oxford Companion to Consciousness* (Bayne, T. *et al.*, eds), pp. 294–296, Oxford University Press
95. Shipp, S. *et al.* (2013) Reflections on agranular architecture: predictive coding in the motor cortex. *Trends Neurosci.* 36, 706–716
96. Sperry, R.W. (1939) Action current study in movement coordination. *J. Gen. Psychol.* 20, 295–313
97. Dijkerman, H.C. (2015) How do different aspects of self-consciousness interact? *Trends Cogn. Sci.* 19, 427–428
98. Guterstam, A. *et al.* (2015) Posterior cingulate cortex integrates the senses of self-location and body ownership. *Curr. Biol.* 25, 1416–1425
99. Plenz, D. and Niebur, E., eds (2014) *Criticality in Neural Systems*, Wiley
100. Engel, A.K. *et al.* (2010) Coordination in behavior and cognition. In *Dynamic Coordination in the Brain: From Neurons to Mind* (von der Malsburg, C. *et al.*, eds), pp. 267–299, MIT Press
101. Buzsaki, G. and Freeman, W. (2015) Editorial overview: brain rhythms and dynamic coordination. *Curr. Opin. Neurobiol.* 31, v–ix
102. McCormick, D.A. *et al.* (2015) Brain state dependent activity in the cortex and thalamus. *Curr. Opin. Neurobiol.* 31, 133–140
103. Singer, W. (2013) Cortical dynamics revisited. *Trends Cogn. Sci.* 17, 616–626 2013
104. Tognoli, E. and Kelso, J.A.S. (2015) The coordination dynamics of social neuromarkers. *Front. Hum. Neurosci.* 9, 563 http://dx.doi.org/10.3389/fnhum.2015.00563.
105. Kelso, J.A.S. (2001) Metastable coordination dynamics of brain and behavior. *Brain and Neural Networks (Japan)* 8, 125–130
106. Tognoli, E. and Kelso, J.A.S. (2014) The metastable brain. *Neuron* 81, 35–48
107. Kelso, J.A.S. (2008) An essay on understanding the mind. *Ecol. Psychol.* 20, 180–208
108. DeCasper, A.J. and Fifer, W.P. (1980) Of human bonding: newborns prefer their mothers' voices. *Science* 208, 1174–1176
109. Voegtline, K.M. *et al.* (2013) Near-term fetal response to maternal spoken voice. *Infant Behav. Dev.* 36, 526–533
110. Rochat, P. and Striano, T. (1999) Emerging self-exploration by 2-month-old infants. *Dev. Sci.* 2, 206–218