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Process and Individuation: The Development of Sensorimotor Agency

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Abstract
I discuss some central ideas of the enactive approach in cognitive science, including the concepts of autonomy, sense-making, and agency, and show the way they are grounded in dynamical systems theory, organizational approaches to biology, and phenomenology. I highlight known and potentially new connections between enactive cognitive science and dynamical and relational perspectives on human development. Taking the notion of sensorimotor know-how or mastery as a particular case, I describe a dynamical formalization of Piaget's theory of equilibration that serves to clarify this notion. The dynamical interpretation also lays the groundwork for a novel concept of sensorimotor agency based on self-sustaining networked relations between sensorimotor schemes. Some of the tools that are used in fleshing out this idea, such as a network representation of sensorimotor repertoires, can be of use for clarifying the processes that underlie developmental variability, apparent developmental jumps, and the role of socially induced disequilibrium in enabling developmental change during adult-infant interactions. The exercise serves to clarify the ontological and epistemological commitments of enactive theory.

Enaction and Developmental Psychology

The enactive approach is an active branch of research in embodied cognitive science with a growing number of publications, research projects, and applications both academic and practical. The origin of this approach is usually agreed to be the publication of the book *The Embodied Mind* in 1991 by Francisco Varela, Evan Thompson,

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and Eleanor Rosch, although the term *enactive* had been used before in psychology with similar senses, for instance by Jerome Bruner (1966). Enactive ideas, in fact, are part of a flow of discontent with the Cartesian ontology and epistemology that still dominate the sciences of the mind, with undercurrents that existed well before the 1990s, including, among others, the phenomenology of Maurice Merleau-Ponty (2012), the works of Jean Piaget, research in autonomous robotics, dynamical perspectives in neuroscience, complex systems thinking, cognitive linguistics, and organizational approaches in biology. The amalgamation of alternatives to mainstream cognitivism into a distinct nondualistic outlook on the continuity between life and mind has expanded over the last two decades into what is beginning to look like a corpus of evolving ideas.

In this context, it is fair to ask if there is the "enactive take" on the problems of developmental psychology. Does it already exist, perhaps under a different name? Are there any *specifically* enactive theoretical commitments, models, hypotheses regarding human development? On first inspection, it would seem that so far enactivists have not been too explicit in attempting to integrate their work with developmental psychology. Apart from various points of reference where developmental studies nourish enactive thinking, there have been only few direct engagements with open problems in psychology, for instance, the problem of developmental variability or the clarification of how sociocultural patterns influence, enable, and even constitute individual becoming.

The existing points of encounter already give some shape to what an enactive view on development might look like. Varela and colleagues make explicit references to the need to understand development not as the unfolding of previously packaged information but as the ongoing interaction between organisms and environments, what Susan Oyama (2000) describes as developmental systems, thus rejecting both nativism and empiricism. Development is manifested as changes in ways of becoming, in the way active bodies are organized in all their dimensions and in the way they relate to their surroundings, drawing for these changes on multiple formative resources, often including the intervention of other bodies. Some of these ideas are further explored in Thompson (2007), but they remain rather general, with an emphasis on implications for biological and cultural evolution. Varela et al. (1991) make an explicit nod to Piaget, finding resonances between the idea that agents bring forth a world of significance and the constructed cognitive structures that emerge through recurrent patterns of sensorimotor activity in Piaget's genetic epistemology. Very much like Thelen and Smith (1994, pp. 322–323), however, Varela and colleagues welcome the dynamical and active elements in Piaget but reject what they perceive as the positing of an adult knower capable of objective rational thinking as the pregiven end point of development.

Another point of contact can be seen in enactive research on intersubjectivity (e.g., De Jaegher & Di Paolo, 2007; Di Paolo, Cuffari, & De Jaegher, 2018), which continuously draws on "interactive" perspectives on social and cognitive development such as Vasu Reddy's (2008) work on the emergence in early infancy of sensitivities to being the object of others' attention.

More recently there has been an attempt at synthesizing several of these strands by formalizing an enactive interpretation of Piaget's concept of equilibration using dynamical systems theory (Di Paolo, Barandiaran, Beaton, & Buhrmann, 2014; Di Paolo, Buhrmann, & Barandiaran, 2017). This work (described later in this article)

was originally motivated by a project to clarify sensorimotor approaches to perception (O'Regan & Noë, 2001) using dynamical systems ideas. This dynamical interpretation has been instrumental in beginning to unpack a new perspective on linguistic agency and language acquisition (Di Paolo et al., 2018).

While work on enaction has been acknowledged by several researchers in developmental psychology, particularly those working in processual or dynamical strands (e.g., Witherington & Heying, 2013; Overton, 2015; Witherington, Overton, Lickliter, Marshall, & Narvaez, 2018), overall, it would seem that it is early days for us to be able to state in clear terms that a crisp enactive perspective on human development already exists. The motivation for this article is to show, however, that there are good signs that we are moving in that direction. After briefly introducing some key enactive concepts, I will spend some time describing the dynamical operationalization of Piaget's theory of equilibration and how it fruitfully combines with enactive ideas of autonomy and minimal agency to give origin to a naturalized concept of sensorimotor agency. This leads to considerations about the nature of action as material events that continuously shape self-sustaining developmental networks of sensorimotor schemes. In the process, I hope to clarify the different roles played by dynamical systems ideas in enactivist theorizing, as well as the particular processual character of enactive ontology and epistemology.

Enaction through Its Questions

Several texts attempt to introduce the basic concepts of enaction (Thompson, 2007; Di Paolo, Rohde, & De Jaegher, 2010; Froese & Di Paolo, 2011; Di Paolo & Thompson, 2014). The central proposal can be summarized as the idea that *embodied agents are dynamically self-constituted networks of precarious material relations with their co-defined environments and that this self-constitution is an achievement that agents sustain through their ongoing activity in the world.* To expand this, I will focus on two related sets of questions enactivists usually have in mind whenever they approach a concrete problem.

The Question Concerning Bodies

Functionalist approaches in cognitive science tend to assume the individuality and integrity of a cognitive agent as unproblematic. They assume, moreover, that there is not much to their status as agents. Functionalists propose cognitive mechanisms to explain a particular performance of interest (perception, memory, decision-making, etc.) but rarely ask the question of how the embodied agent enacting these performances is constituted. Tacitly, they assume this question will be answered by joining all the proposed mechanisms together and somehow making them work as a whole. Even if we accepted the premises of functionalism, we can see how philosophically problematic such an idea is. Are the studied mechanisms really nearly decomposable (Simon, 1969/1996) such that we can safely say their mode of functioning remains the same once we try to integrate them with others? How are all the timescales involved coordinated? How can we account for developmental change and transformation, for the emergence of new skills in this manner? How can we distin-

guish between processes that belong to the agent and external processes the agent engages with but that also enable cognitive performance? Should we limit ourselves to mechanisms instantiated in the brain? In the body? Aren't these questions precisely the problem we are trying to solve? And supposing we end up with a complex architecture of connected boxes, each doing a particular information-processing job, in what sense can it be said that this aggregation of mechanisms constitutes an agent with concerns, motivations, and goals? As we pile up the boxes, at what point does the agent appear?

Functionalism is the default attitude researchers in psychology, neuroscience, and cognitive science adopt when studying cognition. Yet, it has failed in raising – never mind answering – the basic question of what makes an agent an agent; more generally, what makes a body a body. The problem, according to enactivists, is failing to appreciate that this question is *foundational* for understanding embodied minds. In many important respects the issue of agency *defines* the questions that follow; it sketches, in other words, a research program. From an understanding of the norms and conditions that make up a concrete whole body, we can then ask how specific performances are realized and regulated, we can even propose mechanistic-like processes and functional explanations *if* appropriate, but with explicit awareness of their bounded conditions of validity.

For enactivists, therefore, the question of the bodily constitution is conceptually prior to any particular functional account of a cognitive subsystem, even if functional explanations have been abundant in cognitive science and explanations of bodies and agency scarce. Explaining bodies, however, requires thinking in terms of systems, processes, and relations in ways that lead to a different conception of causality from the one that underlies functionalist and mechanistic explanations. Concepts like autonomy and operational closure (described later) provide a glimpse into this conception of causality, which is one that distinguishes, in interventionist fashion (e.g., Woodward, 2003), different kinds of relations between processes, e.g., *contextual* relations (processes that, upon intervention, are found to generally influence one another), *enabling* relations (processes whose defining features require the operation of another process), and *constitutive* relations (processes that conceptually and operationally make up a particular phenomenon; see De Jaegher, Di Paolo, & Gallagher, 2010). As living bodies develop, relations between processes can change between these types: for instance, a reliable contextual factor (e.g., in the environment) may free up the possibility of bodily changes by releasing constraints that otherwise would need to be satisfied actively by the agent, in a way that a dependency is established on the originally contextual factor that turns it into an enabling, necessary condition for a body's current form of life.

Enactivists propose that living bodies are self-individuating material processes that continuously regenerate a set of internal conditions, a topology with multiple cycles of regulation, and a web of relations with their associated environment with the result that they remain viable, organized, and distinguishable. Bodies operate under precarious conditions: none of their constitutive processes is in any way guaranteed to work as supposed to, none of the enabling external relations is unshakeable, and catastrophic change could happen from one moment to the next. Bodies are constantly subjected to disruptions and breakdowns. Such precariousness is, as we will see, the premise from which we can conclude that bodily individuals must also be cognitive agents too, or *sense makers*, and deal with unavoidable lacks and excesses

in order to continue to exist. We notice in passing that precariousness is a negative condition of material processes, one that cannot be captured in functional terms. It describes the fact that any positive property that may sustain a function eventually breaks down. As long as it is available to the body, a function must be actively maintained (and so it remains open to change) until eventually it gets lost.

The self-individuation of living bodies is the subject of several technical contributions in enactive thinking. One central idea is the concept of *autopoiesis* (Maturana & Varela, 1980) which is proposed to describe the organization of all living systems. An autopoietic system is a network of processes of molecular transformation which is organized in such a way that the network is *self-producing* (it sustains and renews the conditions for the operation of the component processes) and *self-distinguishing* (it establishes a topology that defines the network as a unitary whole in relation to the environment). Autopoiesis is a very particular and sophisticated case of self-organization; it is not only ordered patterns that appear and are sustained far from thermodynamic equilibrium, but a system capable (to an extent) of regenerating or regulating the boundary conditions that sustain it.

Organic self-individuation has been later generalized to the concept of *autonomy*, much discussed in enactivist literature (Varela, 1997; Di Paolo et al., 2010; Di Paolo & Thompson, 2014). The idea is more specific than the general notion of self-governance. Autonomy is used to describe self-individuating systems of processes in any domain, not only biochemical transformations. It has been argued that the activity of the immune system is autonomous (Stewart & Varela, 1991), that patterns of neural population activity are autonomous (Varela, 1997), that the distribution of tensions and compressions in the musculoskeletal system could be seen as autonomous, and sensorimotor habits too (Di Paolo et al., 2017).

Each of these types of autonomy must be understood within the context of its respective domain, and not as a repetition of the exact same idea over and over. Nevertheless, the concept of autonomy (technically described by the notion of *operational closure*[1]) is quite powerful precisely because it addresses ontologically and epistemically the process/entity dialectic in a naturalistic manner. Autonomy is grounded operationally in dynamical systems ideas and gives a good illustration of the ontology behind enactive thinking. The constituent "elements" of autonomous systems are always processes, organized patterns of change, intensities, rhythms, and relations.

[1] As we have said, relations between processes may undergo organizational changes, e.g., turning contextual factors into enabling conditions. In the concept of operational closure, we see enabling relations that form an organization become constitutive relations once this organization is established. An autonomous system is an operationally closed system under precarious conditions (e.g., Di Paolo, 2009; Di Paolo & Thompson, 2014, pp. 69–72; Di Paolo et al., 2017, pp. 111–116). Technically, operational closure means that among the enabling conditions for any constituent process in the system we will always find one or more processes that also belong to the system. And, in addition, every process in the system is an enabling condition for at least one other constituent process, thus forming a closed network of enabling relations. There are no processes that are not enabled by other processes in the network – which does not mean, of course, that external processes cannot also influence and enable the constituent processes, only that such external processes are not part of the operationally closed network because they are not themselves in turn enabled by the constituent processes in the system (sunlight enables photosynthesis in plants, but plants do not enable the existence of the sun). In addition, all constituent processes operate under precarious conditions, meaning that they would normally tend to run down unless regularly sustained by the operation of the network (i.e., enabling relations need to be sustained in time; they are not only historical antecedents). A typical case of a precarious operationally closed system would be an autocatalytic cycle of chemical reactions, a more sophisticated case a living cell.

They are moreover subject to mutual constraints that affect their viability. An "entity" makes its appearance whenever processes are organized in such a way that they result in an autonomous unity (for instance, a living body). The resulting whole is neither an epiphenomenon nor a magical source of top-down causal powers. It is the concretization of constituent, enabling, and contextual processes that, through shared history, settle into operational, functional, and "existential" relations of mutual dependence. Crucially, the individuation of this entity is not arbitrary; it does not rely, for example, on the stability of processes or on slowness of change. Slow-changing processes can help us distinguish material objects, but do not by themselves constitute autonomous bodies. Objects tend to endure by staying the same, bodies sustain themselves by undergoing constant change.

The Question Concerning Meaning

The answer to the question of what constitutes a body in terms of autonomous self-individuation is itself "self-moving." It directs our attention to another set of questions. If the conditions for self-individuation are precarious, how do living bodies get so good at keeping themselves alive? Why don't they run down like self-organizing Bénard cells as soon as we turn off the heating and let the oil cool down?

Toward the end of his life Francisco Varela explored the idea that there is an intrinsic relation between autonomy and *sense-making*, understood as the orientation of organisms towards what is meaningful for their form of life, e.g., sources of nutrients, shelter, risks, predators, and so on. He suggested that the very condition of autonomous self-individuation introduces an evaluative gradient on relations with the environment (Varela, 1997; Weber & Varela, 2002). The body as a process of material self-construction is a source of *vital norms* (Merleau-Ponty, 1942/1963; Thompson, 2007) in that this process is the origin of material needs (e.g., food and water) and can be put at risk by negative encounters (e.g., ingesting something poisonous). Vital norms are defined in terms of the conditions that must obtain for an organism to remain viable. Not only the actual and present conditions that obtain in the organism and the environment at any given time, "but also in the sense of conditions that need to be actualized (effected or procured) – in other words, *virtual conditions*" (Thompson, 2007, p. 74). Even in the simplest forms of life we find this orientation towards significance, as we observe bacteria following sugar gradients, avoiding noxious chemicals, seeking favorable conditions of temperature and pH. These encounters are normative in that their outcome makes a difference; the organism's intervention may fail or succeed to different degrees in actualizing the conditions that contribute to its viability. Observing the behavior of organisms is then like following living signs and arrows that point to processes of intrinsic sense or value for the organisms themselves. These observations are so basic in the study of animal behavior, so integrated into the research methodology, that it is easy to miss the fundamental entailment they make apparent, i.e., the fact that precarious bodily individuation is a condition for grounding meaning or that, using philosophical jargon, bodies naturalize the mind.

This is the question concerning meaning. Why do living bodies care? Why doesn't even the most sophisticated robot or chess-playing program show any signs of giving a damn about falling down the stairs or winning a match?

Varela's proposal for an answer to the question of meaning requires some fine-tuning but is basically sound. By the very fact of being alive, organisms are also sense makers. This is one of the meanings enactive theorists give to the continuity between life and mind. Sense-making is a rather general kind of engagement between organisms and world. It is an umbrella term that describes a situation in which a body responds adaptively to some aspects of its dynamical coupling with the environment in terms of the implications for its ongoing viability. The capability for adaptive response (adaptivity) need not always result in an act of regulation (adaptation), but it is not just a passive capability-in-waiting either. Sense-making is always active in that it entails an ongoing sensitivity to the current situation's consequences for viability and a readiness to respond accordingly, in other words to the relevant actual and virtual conditions. The extent of this sensitivity and readiness depends on the organism, of course. It is not unlimited. The idea of adaptivity is made operational using dynamical systems concepts (such as state trajectories and boundaries of viability sets), and it is necessary, in combination with the condition of autonomy, to speak of sense-making (Di Paolo, 2005). Even so, adaptivity is not just an abstract property but an active combination of powers and sensitivities that operate following vital norms. This is another way in which enactive conceptions of causality differ from functionalist and mechanistic models. The operation of adaptive processes relies on the actual state-dependent conditions of the living body, but they both intervene in and are regulated by the virtual, not-yet-actualized possibilities present or created in a concrete situation.[2] Together with Hans Jonas (1966), many enactivists accept that all of this also entails an interior dimension of *caring* for the outcome of acts of sense-making, a life of nonindifferent sentience. Indeed, at the most basic level, it is obvious that the continuous existence of an organism is at stake. But this situation is rather general and applies to all kinds of norm-following, all forms of minded activity, although the connection between cognitive performance and the viability of a form of life can be more indirect, more mediated than in the case of obtaining nutrients to survive. We use the term sense-making therefore to refer to the most general form of mindedness. Whenever there is autonomous self-individuation capable of adaptive interventions, acts of sense-making are taking place. This is the case for all known living organisms. Conceptually, the idea of sense-making does not introduce as yet any distinction between action, perception, emotion, or cognition. Such distinctions become apparent as differences in ways sense-making that are afforded by different forms of life, different embodiments, histories, and situations, i.e., as we evaluate the effect of qualitative changes in the kinds of autonomous individuation undergone by living bodies.

[2] Enactive explanations, as we have seen, differ from functionalist explanations also in that they attempt to identify via observer interventions the types of relations between phenomena (contextual, enabling, constitutive). Enactive explanations also take seriously not only the reality of actualized states, but also of virtual ones (possibilities, risks, options, powers, dispositions, etc.). A third difference we should mention briefly (although it is more or less implicit in this discussion) is the concrete situatedness of the knower/researcher as an embodied being in the context of the phenomena she wishes to explain. Explanations are therefore dependent on a set of vocabularies, interests, skills, habits, projects, etc. (Garfinkel, 1981). A community of human knowers is also a historically situated and embodied community. This often leads to enactivists adopting reflective perspectives on the possibility of knowing as a community of embodied minds subject to conditions of self-reflective, experiential, intersubjective, and practical coherence in the activity of research. No scientific explanation is neutral, and enactivists attempt to make this nonneutrality explicit. For this reason, phenomenology and social criticism are important instruments in the enactive explanatory toolbox.

Equipped with the concepts of autonomy and sense-making, we may go back and ask: what makes a body also an agent? Having a clear position on this issue, together with the question concerning meaning, should be at the basis of any science of the mind. Yet, functionalist and dualistic frameworks do not take the problem of agency seriously and, as a consequence, the issue has become contentious, sometimes intuitively recognized as important, sometimes discarded as cryptic and unscientific; in any case, hard to theorize about. Is agency simply a superfluous gloss on action? Is it a mystical category for an entity that controls and directs performance from above? We will come back to these issues later, but from an organizational perspective, our first step should be to attempt to circumscribe what we wish to capture when we speak about the idea of agency (activity, perspective, powers, norms, etc.) and see whether we can ground that idea in an operational, dynamical characterization. In a way, this question is already answered as soon as we see the mutual dependencies between autonomy and sense-making.

Whenever we speak of an agent (in the context of psychology) we are implicitly concerned with three requirements: (1) *individuality:* we refer to an agent as a *distinct center of activity*, different at least in some senses from its environment; (2) *asymmetry:* apart from being dynamically coupled with the environment, agents have the power to sometimes engage in *modulating* the conditions of this coupling, and doing so actively and with regularity; (3) *normativity:* agents modulate their relation to the environment *according to norms*, which turn these modulations into *regulations*, i.e., asymmetrically induced changes in the current situation that adaptively avoid or respond to threats to sustained viability. It can be shown that a precariously individuating body who is also a sense-maker fulfills these three requirements as argued in Barandiaran et al. (2009) and Di Paolo et al. (2017). Such a body therefore *is* an agent. Again, this dynamically grounded concept of agency should be seen as the minimal expression of a range of sophisticated possibilities.

In fact, in the case of human bodies, there is no unitary dimension of self-individuation but several, with complex, entangled relations that can and do change during development. We can distinguish an *organic* dimension of embodiment instantiated as cycles of metabolic self-individuation and regulation of organic integrity and powers. There is also a *sensorimotor* dimension instantiated as loops of action and perception as well as internal autonomous patterns of neural, hormonal, and musculoskeletal activity. There is also an *intersubjective* dimension concerned with transpersonal individuation, ways of interacting and relating to others, participatory sense-making (De Jaegher & Di Paolo, 2007; De Jaegher et al., 2010), and patterns of social becoming and identity. These forms of individuation become highly entangled during development, and their relation is not simply one of "progression" (organic – sensorimotor – intersubjective). As we shall see later, sensorimotor individuation can be activated and shaped by social interactions. Similarly, organic individuation is modulated by lifestyle choices such as food preferences or how we confront trade-offs in dealing with an illness, and by social injunctions, living conditions, modes of economic production, etc. (e.g., Lewontin & Levins, 1997; Mol & Law, 2004). All of these dimensions, to complicate matters, are radically changed as human beings participate in linguistic communities (Di Paolo et al., 2018). Autonomy, sense-making, and agency are at play in each of these dimensions. Sometimes a single concrete body becomes a locus of overdeterminations that emerge as internal conflicts (this is why it is difficult to change "bad" habits). Navigating these conflicts is an ongoing open-

ended task we face daily and the paths we take (together with other human bodies) are multiple and created by the very activity we participate in. This is why enactivists insist that through our activity we *bring forth a world*. If by the very nature of precarious material individuation, living bodies are active and restless, this is even more the case for human bodies, where organic, sensorimotor, and social individuation converge, giving rise to open-ended braided threads of meaning making, which are shaped by individual and collective activity in path-dependent, historical patterns throughout our lifetime.

Sensorimotor Agency and Equilibration Theory

There is an interesting back-and-forth movement in the short history of enactive thinking between concerns for sensorimotor and organic aspects of embodiment. Varela, Thompson, and Rosch (1991, p. xv) formulate their work as a continuation of Merleau-Ponty's research program, and most of the book is dedicated to a phenomenologically informed critique of functionalism and the sketching of a nonrepresentationalist alternative focused on embodied action and perception, and the embodied self. Enaction is pitched at the level of sensorimotor networks (e.g., p. 206). But Varela's previous research on autopoiesis and autonomy is an undercurrent of this book and resurfaces in subsequent work. These and later developments have followed what we might call a *minimalistic* stance, attempting to build new concepts using minimal forms of cognition first (bacteria are paradigmatic cases of minimal enaction), then drawing general lessons from these efforts to more complex situations.

The advantage of minimalism is that it affords the much needed exercise of thinking in terms of wholes and relations, something we are not used to and that is hard to do if we try to tackle very complex situations head-on. But we cannot expect enactive work to cover the spectrum of complexity "from cells to culture" (Froese & Di Paolo, 2011) using ideas developed and tested *only* in minimalistic cases of agency and sense-making. This has been a justified worry of many commentators of the enactive project since the beginning, many of whom declare themselves certain that as soon as we move from simpler scenarios to complex human minds, we will need to bring back representationalism in classic or updated forms, simply because *there is no alternative* (Dennett, 1993; Clark & Toribio, 1994; Wheeler, 2005, and others).

On the one hand, we should always be cautious of arguments by default. Lack of imagination does not constitute proof of impossibility. But on the other, skepticism is justified if we cannot advance toward more explicit and operational proposals to explain "human level" cognition. Knowledge of what is possible is always expanded by action. Some options *become* possible only if they are pursued with certain unrelenting persistence, in this case by attempting to theorize what functionalist common sense says cannot be theorized: an explanation of human minds from the ground up that does not demand mental models or representations or follow the computer metaphor in any way. This attempt is what motivates recent work addressing some specificities of the sensorimotor, social, and linguistic dimensions of embodiment (Di Paolo et al., 2017, 2018). Because they finally bring enaction into much closer dialogue with developmental psychology, I briefly discuss in this section two connected examples of such work: a dynamical systems interpretation of Piaget's theory of equilibration and the development of a concept of sensorimotor agency.

Equilibration from a Dynamical Perspective

Di Paolo and colleagues (2014, 2017) elaborate a formalization of Piaget's equilibration theory (Piaget, 1936, 1947, 1975; Boom, 2009, Chapman, 1992). The original motivation for this formalization was the need to provide an account of perceptual learning that would clarify the concept of *mastery* as used in the sensorimotor approach to perception (O'Regan & Noë, 2001; Noë, 2004) but the result has implications beyond this particular problem. According to this approach, perceptual experience stems not from possessing the right kind of internal representations but from the mastery of sensorimotor contingencies. This mastery is the know-how our bodies have that certain patterns of movement will induce certain sensory changes. This is proposed as sufficient to explain the phenomenology of perceptual experience. There are various issues that need clarification with this idea. One of the main issues in need of a proper explication is the concept of mastery. What exactly does it mean to possess mastery of sensorimotor contingencies? We proceed to answer this question by showing that it is possible to define sensorimotor contingencies using the language of dynamical systems and provide an operational definition of mastery. Here enters a dynamical and world-involving interpretation of equilibration as the ongoing transformation of sensorimotor schemes and relations between sensorimotor schemes.

We understand sensorimotor schemes as "reusable, interlocking, organized sets of coordination patterns between body and environment" (Di Paolo et al., 2017, p. 81). A scheme, therefore, entails a concretely organized set of coordination patterns, mutually adjusted in timing, intensity, precision, etc., and these coordination patterns always obtain from a transaction between body and world. Consider the acts of opening a door, peeling a mandarin, shuffling cards, plugging a phone to recharge its battery, etc. These are sensorimotor schemes and as the examples suggest, they are rarely produced in isolation. They are always embedded in a network of other schemes that constitute the relevant processes of a particular activity (see, e.g., Bernstein, 1996).

Sensorimotor schemes are interesting because they provide a mesoscopic level between, on the one hand, anatomy, physiology, and neurodynamics and, on the other, notions of normativity, skills, habits, styles, and intentions. Sensorimotor schemes can be projected onto subpersonal and personal levels without collapsing one vocabulary into the other. As well as being a concept grounded in sensorimotor coordination patterns, themselves describable using the language of dynamical systems, schemes also imply a certain normativity. They are part of actions that may succeed or fail, be more or less efficient, elegant, relevant, etc.

Strictly speaking, sensorimotor schemes are not something a body possesses but are always the result of an encounter between body and world. There is convenience in speaking of an agent having a sensorimotor repertoire and being able to enact this or that scheme, having certain competences, or possessing such and such skill. This is appropriate provided it is always understood as a shorthand for the enabling bodily conditions for actualizing sensorimotor schemes. This is not a minor point for a world-involving approach, where the world is not merely a contextual causal factor or a source of data for internal processing. The world is materially co-constitutive of sensorimotor performance, sometimes in subtle, sometimes in strikingly obvious ways (e.g., surfing). Having powers and sensitivities required for action, in other words, is only half the story. The other half is access to suitable accompanying condi-

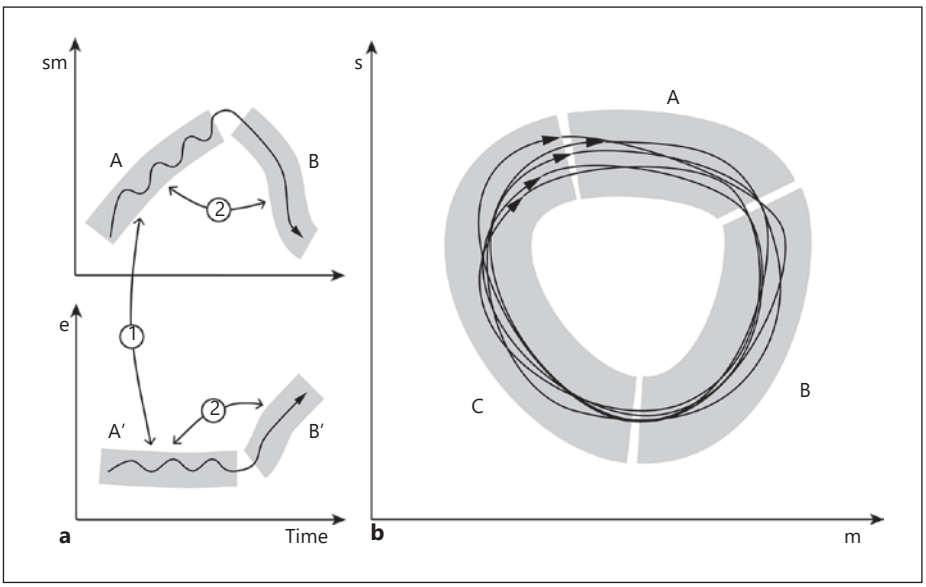


Fig. 1. a Sensorimotor (sm) and environmental (e) trajectories in time illustrating the stability and transition conditions in an equilibrated sensorimotor scheme. Individual trajectories are shown as curves and the sets they belong to as gray bands. The stability condition (1) indicates that sensorimotor and relevant environmental trajectories remain within their respective classes A and A′ when co-occurring. In the transition condition (2) the trajectories of the coupled system in A × A′ lead to the next coordination stage in the cycle, B × B′. Disequilibrium would obtain from a failure of either condition, and the trajectories would escape from the gray zones (the current equilibrated state). **b** Projection onto sensory (s) and motor (m) coordinates showing many instantiations of a circular scheme.

tions surrounding the agent, which in our world-involving perspective must themselves be active and concrete and not merely formal (e.g., a wave to surf on rather than an array of visual and haptic information; a loud enough platform rather than an abstract right to free expression, and so on).

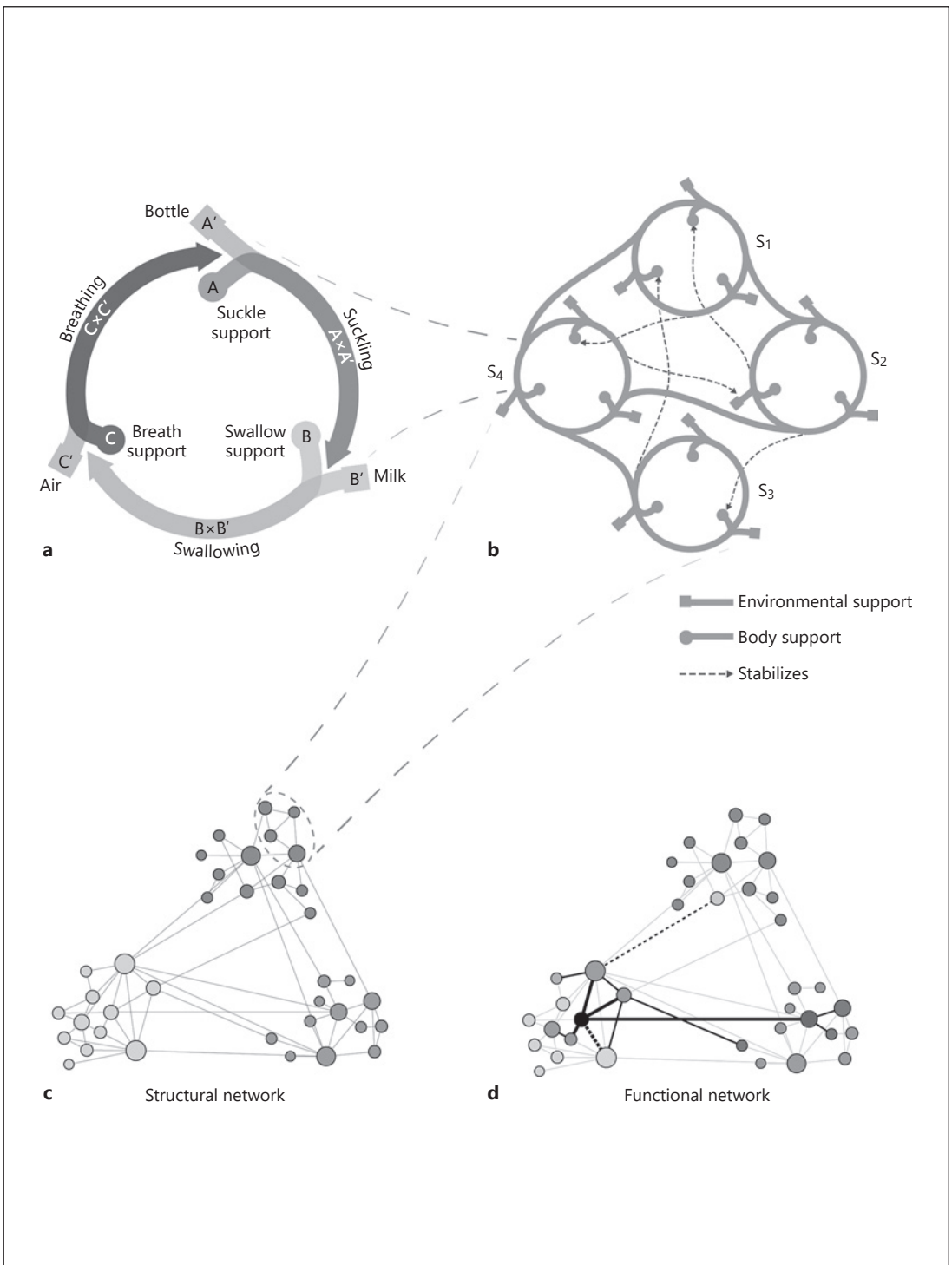
Schemes are shaped by experience through processes of assimilation and accommodation, driven by breakdowns and plastic recoveries. For Piaget the organization of sensorimotor schemes was primarily circular, but not exclusively so. This permitted him to see circular and rhythmic sensorimotor processes, such as a baby breastfeeding, as instantiating a norm in their repetition in addition to other relevant biological norms (e.g., nutrition). Embodying the sensorimotor norm is dynamic, namely an array of several coordination patterns bearing the right relations to one another so they are able to return to the starting point and reinitiate the cycle. With respect to this condition some events can count as obstacles or lacunae – that is, coordination may be disrupted because of an environmental impediment or it may lead to an incorrect transition from one part of the cycle to the next, signifying some lack of grasp of the situation. If and when such obstacles and lacunae are overcome by plastic changes in sensorimotor schemes, they are said to be equilibrated. This

may include the possibility of fully novel schemes emerging out of the differentiation of older ones.

What does the dynamical interpretation of equilibration consist of? We can describe the component coordination patterns as the joint occurrence of trajectories of the agent-environment coupled system projected onto sensorimotor and environmental state spaces. These occurrences must fulfill certain conditions, and we describe these in set-theoretic terms. Figure 1 summarizes the main ideas. We see on the right panel (Fig. 1b) a depiction of trajectories in a simplified sensorimotor space forming cyclic movements corresponding to enactments of a circular sensorimotor scheme (e.g., a baby drinking from the milk bottle, where each phase corresponds roughly to suckling, swallowing, and breathing, see also Fig. 2a).

Instances of the cycle are not identical. What makes them belong to a same organized scheme? Two conditions, which are depicted in Figure 1a. The stability condition (1) specifies that trajectories projected on sensorimotor and environmental spaces are mutually stable with respect to a class of sensorimotor and a class of environmental states, respectively A and A′ (shown as gray bands in Fig. 1). The transition condition (2) specifies that the enactment of a coordination $A \times A'$ leads to a new coordination $B \times B'$ which corresponds to the next stage in the cycle. The scheme is considered equilibrated if sensorimotor trajectories and their grouping into classes converge and if it is reliably enacted in the right circumstances. A scheme enters disequilibrium whenever a previously converged situation (between classes and instances) is disrupted, which means that conditions 1 or 2 or both fail (trajectories would move out of the gray regions in this case). The first kind of breakdown (loss of condition 1) corresponds to obstacles and the second (loss of condition 2) to lacunae. In the case of obstacles, the coordination cannot be enacted as in previous instances (it falls outside the $A \times A'$ zone), which may be due to changes in environmental or bodily circumstances (an object proves to be much heavier than it looks, or a pulled muscle makes lifting it very painful). In the case of lacunae, the coordination pattern is enacted but it does not lead to a transition to the next stage in the scheme. It leads to some other condition indicating that there is something about the situation that the agent does not currently grasp. Recovery from such cases leads to equilibration via plastic changes in the body and/or in the environment such that the disequilibrated scheme achieves a new (temporary) condition of convergence (according to the relevant norms). This process extends to changes in the relation between whole sensorimotor schemes as they are frequently enacted within the frame of a given activity.

The mathematical details of this operationalization can be found in Di Paolo et al. (2017) together with discussion of general principles that can lead to open-ended equilibration. For the most part, this restates in dynamical terms the central ideals of Piagetian equilibration. There is a more explicit emphasis on the role of the environment (which can include the activity of other agents) beyond being primarily a source of data or resources. This avoids risks of an internalist and prescriptive interpretation. For instance, when considering the sources of plasticity that support accommodation, there is in principle no reason to confine these to neural or bodily changes in the individual. The surrounding conditions may also be altered by the agent, by others, or by the environmental processes themselves (e.g., spatial arrangements in a working space) and help induce new equilibration. Something that also differs from the Piagetian account is that from the enactive perspective any kind of perceptual learning or



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(For legend see next page.)

development of a sensorimotor skill is always a move from a whole world of meaning into another, never a move from a meaningless, dispersed, realm of sensations into illuminating sense. This was one of the criticisms made by Merleau-Ponty (2010) of the Piagetian program on phenomenological grounds. At least at the early stages Piaget's theory would seem to postulate a state of meaningless sensations that only through equilibration are given sense. In our view, equilibration moves from worlds of significance to new worlds of significance. It is never meaningless, although in phases of conflict, breakdown, and disequilibrium, or in uneven development, appropriate forms of sense-making may still be absent, and the world can become conflictive and appear as lacking sense. Even in such cases, lack of sense is only understandable precisely because of a conflict with a whole frame of meaning-making that is already in place.

To come back to the question of mastery, we can now define it in terms of equilibration as *both* the agent's sedimented (equilibrated) organization of relevant sensorimotor schemes *and* the active openness and capacity to attempt to overcome new sensorimotor breakdowns.

Sensorimotor Agency: A Network Perspective

The dynamical account of mastery as past and ongoing equilibration within and between sensorimotor schemes suggests a solution to another problem: is sensorimotor life reducible to organic life, or are there distinctly sensorimotor kinds of selfhood and agency? As we described earlier, the logic of organic self-individuation entails a concern with vital norms (nourishment, shelter, avoidance of harm, and so on). But personal experience shows that we are not always concerned directly or indirectly only with biological survival. For instance, we care about actions being dexterous as opposed to awkward, we indulge with kinesthetic pleasure in our powers for moving as in dance and physical exercise, we sometimes need to take a break from sitting down at the desk and go for a walk and look at landscapes, we suffer in situations of sensorimotor monotony. This would suggest that in considering sensorimotor sense-making (action, perception, emotion) we need to provide an account of *sensorimotor*

Fig. 2. Sensorimotor schemes and their relations at increasingly larger scales. **a** A scheme for drinking from a milk bottle composed of three sequential coordination patterns (e.g., $A \times A'$) each supported by processes on the agent side (A) and on the environment side (A'). **b** Four schemes (S_1 to S_4) bearing horizontal relations (thick gray connecting lines) indicating relations of priming or inhibition and vertical relations (dashed black arrows) indicating the stabilization of support conditions in the body or in the environment. **c**, **d** A partial view of a hypothetical sensorimotor network. Nodes represent sensorimotor schemes and links their structural and functional relations. They are arranged into three clusters corresponding to strongly codependent schemes. **c** Links indicate structural relations between schemes. **d** The functional connectivity at a particular moment is shown. The currently active scheme is shown in black. Its activation makes transitions to other schemes more likely (thicker solid lines) or less likely (thicker dashed lines). Some neighboring schemes become preactivated or inhibited (shown here as a change in shade), which in turn may lead to modulation of their own transitional links. From Di Paolo et al. (2018).

norms, implying therefore that self-individuation processes other than purely organic ones may be at stake.

The picture becomes clearer once we drop the tendency to look at sensorimotor schemes abstractly and consider the way they relate to each other. Sensorimotor schemes organize themselves into several kinds of relations of support, priming, inhibition, and so on. Each enacted scheme is linked in various ways to other schemes, for instance, action possibilities surrounding a current act that are inhibited, preactivated, or in some other way virtually present. Some of these links are functional as in the case of schemes that need to be enacted in some combination in parallel or in sequence (*horizontal* relations depicted by thick lines in Fig. 2b), some links are enabling, as in the case of schemes that influence the bodily or environmental conditions for other schemes to take place (*vertical* relations, thin dashed arrows in Fig. 2b).

If support conditions are materially precarious (like a metastable environmental process that requires our action to continue, or a neuromuscular circuit subject to decay unless reused) regular enactments of the supporting schemes are necessary for these conditions not to degrade and for the schemes they support not to disappear from the repertoire. When these vertical relations form a closed network, we may speak of *habits*[3], that is, groups of schemes that become self-supporting as a consequence of regular enactments, and that in turns promote future enactments.

There is a two-way influence between, on the one hand, concrete action and events in the world and, on the other, the organization of schemes themselves and their mutual relations. This becomes apparent in the operationalization of equilibration (remember the convergence between *instances* and *classes* of sensorimotor trajectories). Because of this, each action leaves a trace not only in the environment, but also in the whole network of relations between schemes. The enactment of a scheme alters or reaffirms a set of relations to many other schemes. These relations may ultimately form a closed network of mutual enablement that is reasserted by every successful act and challenged by every breakdown, through spreading processes of equilibration within and between schemes. Or to be more precise, each act is *successful* from a sensorimotor normative perspective if it helps reassert the organization of the network of sedimented schemes or a case of *breakdown* if it challenges the closure of this network.

Once we can show that the conditions of precarious individuation can obtain at the sensorimotor level, we can apply an argument analogous to the one regarding the links between sense-making and the individuation of the organic body. A self-sustaining network of equilibrating relations among sensorimotor schemes (a "bundle of habits" to use the Jamesian image) fulfills the three requirements for agency: it is self-individuated as an autonomous system, it regularly induces asymmetric modulations of the dynamic coupling with the environment, and these modulations follow norms that correspond to the viability of the sensorimotor network itself.

This idea changes our conception of what counts as a body. The enactive conception of living bodies is dynamic and relational and serves as an example of a

[3] From this definition, it should be clear that we do not mean habit in the sense of blind automatism. The concept of habit has a rich and complex history (Barandiaran & Di Paolo, 2014; Carlisle, 2014). Our meaning here is close to the use of the idea in pragmatism (e.g., James, 1890; Dewey, 1922). For further discussion of the resonances between pragmatism and the enactive approach, see Gallagher (2017).

process/individuation dialectic. But, up to this point, we could still think of bodies more or less conventionally as bounded anatomical/physiological entities, more or less the way they look in a photograph. Sensorimotor bodies are not *just* organic bodies. They are made up of networks of relations between precariously equilibrated sensorimotor schemes; they are organized patterns of enactments, powers, and sensitivities. Sensorimotor norms establish how well a given act coheres with other acts, with the current situation, and overall, with the particular, historically developed sensorimotor *style* of the agent. Thus, it is *acts themselves* that constitute a sensorimotor agent (see also Korsgaard, 2009, and Langer, 1967) and define a sensorimotor body as an ongoing process. Bodies are therefore not just centers of active engagement with the world, they are, in a very strict sense, *composed* by the traces left by enactments themselves, something a photograph may hint at, but does not quite capture.

The reassertion of a sensorimotor identity that occurs with every act is at the basis of our sense of agency, of having powers and sensitivities. If an act or event affirms or challenges sensorimotor identity, this is often *felt* directly. We do not need to represent this fact in order to tell whether an act is our own or not. Pathologies in the sense of agency may also be understood in these terms (Buhrmann & Di Paolo, 2017).

As a result of a history of mutual equilibration, schemes in the sensorimotor network form clusters and develop into what we may call *activities* or *microworlds* (Varela, 1992). These clusters correspond to regional powers, sensitivities, and norms that together make up a cognitive ecology of practices (Hutchins, 2010). The bottom row of Figure 2 shows a subregion of a hypothetical network of sensorimotor schemes. As we will expand next, this metaphor can be useful, for instance, in following organizational changes during development. Nodes represent sensorimotor schemes and link their relations. The network can help us see the difference between *structural* relations at the developmental scale (e.g., schemes that when enacted affect the support structures of other schemes) and *functional* relations at the behavioral scale (e.g., when one scheme is currently activated, we can represent what other schemes are preactivated or inhibited as a consequence). The network metaphor helps us think simultaneously about the history of sedimentation and the current powers and sensitivities of a sensorimotor agent. Single nodes may appear or disappear, and whole clusters may coalesce or disperse during development. Sensorimotor networks can change in time due to, e.g., physiological, neural, and anatomical changes, lack of use, injury, alterations to the environment, lack of resources to produce equilibration, environmental supports, access to technology, and the participation of others.

Weaving the Developmental Web

The enactive approach – rapidly sketched in the previous sections – gives the idea of agency its due in terms of operationalization without reducing it to behavior or positing extraneous entities. Agency makes a difference. It is not a conventional ascription by external observers or a regulative Kantian notion beyond scientific reason. All of the elements in this conception are grounded in dynamical concepts, themselves tested descriptions of organized material processes. The approach also

provides us with tools that can serve to continue the dialogue between embodied, ecological, and dynamical perspectives on development.

At a general level, there is evidently much in common between the enactive picture and various related critical strands in developmental psychology that advocate processual, relational, and nondualistic perspectives. Commentators have remarked on these resonances (e.g., Overton, 2015; Witherington et al., 2018), and the question of agency has been part of these discussions (Witherington & Heying, 2013). As I hope will become clear in this section, the enactive perspective is not limited to just one dimension of embodiment but is capable of theorizing the mutually enabling relations between development and sociomaterial and cultural patterns, a theme that is also very much the focus of concern for developmental psychology (e.g., Maynard, 2008; Adolph, Karasik, & Tamis-LeMonda, 2009; Stetsenko, 2017; Adolph & Hoch, 2019).

The multiscale character of the enactive account, spanning different orders of magnitude and timescale, also resonates with the suggestion that development relies on extended brain-body-environment networks (Byrge, Sporns, & Smith, 2014), from intrinsic brain dynamics and sensorimotor activity to histories of engagement with the world. There is strictly speaking no single locus for development, which by no means implies there are no clear processes of individuation at play, entities that emerge, relate as wholes to other entities, and act, and thereby shape, how development occurs.

Treating sensorimotor repertoires from a network perspective is helpful for making sense of variability, divergences, convergences, and qualitative changes in development. The idea of a network of schemes has been proposed before in neuroscience (e.g., Arbib, Érdi, & Szentágothai, 1998) and neuroethology (Fentress, 1983). Similarly, in their dynamic skill approach, Kurt Fischer and colleagues advocate changing the "ladder" metaphor of development for one of situated developmental webs (Fischer, 1980; Fischer & Bidell, 2006). This shift facilitates accounts of developmental discontinuities as produced by otherwise homogeneous underlying principles and dynamics. The same question has been considered using descriptive/phenomenological dynamical models (van Geert, 1998); the network perspective can be interpreted as providing further operational justifications for such models. In the network view, apparent discontinuities in development do not require extra mechanisms other than the sorts of equilibration that we have described. It is not difficult to picture equilibration events sometimes as a node in the network splitting into two different schemes, sometimes as links between nodes appearing or disappearing, sometimes as a node vanishing. What is interesting is that these "microevents" are helpful for explaining events at a larger scale, for instance, the formation of clusters of tightly related schemes, the fission of clusters into different but related activities (e.g., eating a snack at home vs. having dinner in a restaurant), the formation of superclusters indicating genres of activities (e.g., gardening), the fusion of initially distinct clusters marking the relatively rapid emergence of a whole new skill out of the mutual adaptation of existing ones, and so on.

By this we do not mean to reduce development to microevents. Microevents are facilitated, enabled, or impeded by larger configurations in the sensorimotor repertoire where not only a particular history has sedimented, but also possibilities, opportunities, intensities, and speeds of change are constrained by the whole. For instance, self-sustaining habits can sometimes promote and sometimes enter into con-

flict with the development of new skills. There is a bottom-up and top-down traffic in developing networks (this is a logical implication of the idea of sensorimotor autonomy).

Network events can describe known cases of developmental path variability and dependence. For instance, the development of reaching in infants has been shown to depend on idiosyncratic factors such as body size and movement energy (Thelen, Corbetta, & Spencer, 1996). To achieve the appropriate speed and accuracy for a successful reach is a different problem for different infants. It is approached by different interactions of nonreaching schemes such as bringing the hand to the face or moving the arms rhythmically. Each infant, with her particular combination of resources, must "walk a different path" in order to reach successfully, e.g., slowing down very energetic movements to improve accuracy or speeding up very slow movements to increase reach. We can see that if successful reaching is represented in the network model by the appearance of a few mutually equilibrated schemes, this event can have different antecedents (a split from an existing cluster, the convergence of previously quasi-independent nodes, etc.). The idea is also applicable to other cases of path dependence such as learning to read in first-, second-, and third-graders (Knight & Fischer, 1992) and the variety of pathways to crawling in infants (Adolph, Vereijken, & Denny, 1998).

As many have convincingly argued, developmental path dependence and variability should be taken as primary data, not as deviations from a norm (e.g., Molenaar, 2004; Rose, Rouhani, & Fischer, 2013). Human variability is a natural expectation of the enactive model. Development, in the sense of changing patterns in the organization of sensorimotor repertoires, inherits the processual nature of schemes, which are the coordinated encounter between bodily and environmental processes. For humans, these concrete encounters are highly contingent on factors such as the availability of sociomaterial resources, the nature of behavior settings, the cultural embeddedness of parenting practices, attitudes towards gender, etc. Moreover, what develops is, as we have established, also an *agent*, with motivations and personal history, who is to an extent able to regulate, accommodate, resist, and sometimes overcome external constraints on action, emotion, and thought. Development is also, as many have remarked, cumulative and enabling in the sense that new sensorimotor patterns create new worlds by opening up new sources for engagement (Campos et al., 2000). Human bodies develop in deeply contingent ways, such that to be embodied is always already to be different from other bodies. It is almost impossible to conceive of anything resembling a general developmental norm other than by abstracting out of multidimensional skills some particular dimensions that are deemed of concern by a specific culture and social organization.

To appreciate in some detail how this multiplicity of factors makes human development a highly nonergodic process, we may take a brief look at the case of adult-infant interactions as sources of developmental change. A much studied case concerns the passage from what Trevarthen and Hubley (1978) call primary intersubjectivity (affective social tuning, early reciprocal engagements between infant and caregiver) to secondary intersubjectivity (e.g., shared attention to objects). Evidence correlates dyadic and triadic competences at different stages of development (e.g., Striano & Reid, 2006). But what exactly are the relations between individual changes in sensorimotor repertoires and interactive engagements with others? A typical assumption is that the social environment affords sources of complexity and that the

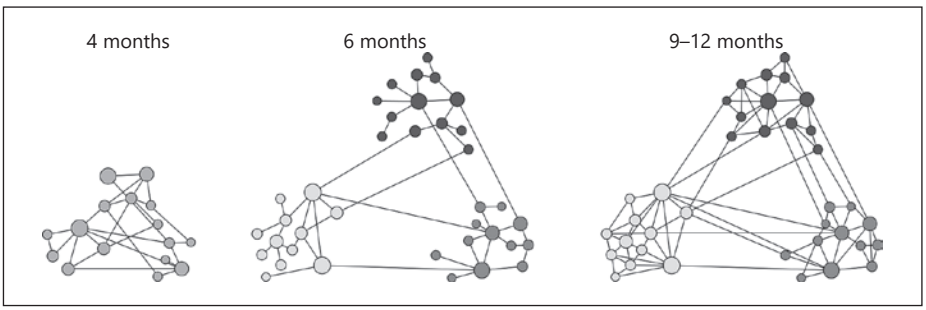

Fig. 3. A developing sensorimotor repertoire during mother-infant interactions in the first year (hypothetical network representation). At about 4 months of age, the infant's sensorimotor schemes are tightly organized into synergies. As the mother solicits bids for attention to herself and other objects, these schemes diversify into new, loosely linked clusters (6 months). The mother now encourages integration of these schemes by sustaining attention and manipulations on single objects. This results in the network growing increasingly consolidated as the schemes for attention, object manipulation, shared attention, and social acts get progressively integrated (12 months).

developing infant gets increasingly better at coping with this complexity. This is still a very individualistic view that contrasts with our world-involving approach in which the world (specifically the social world) acts as engine and guidance of developmental processes.

Studies of changing patterns of mother-infant interactions (in Western middle-class households) validate this idea. During the first year, changes in sensorimotor organization correlate with changes in interactive patterns between mothers and infants (de Barbaro, Johnson, & Deák, 2013). Infants tend to engage with objects in a very synergistic manner at 4 months of age, focusing all sensorimotor modalities on a single object. This is followed, at about 6 months, by an opening to decoupled engagements, such as looking at the mother while grasping a toy or manipulating two objects simultaneously. During this transition mothers actively attempt to break the infant's focus on a single object by soliciting eye contact, showing them other toys they can play with, and so on. As the infant's attention is now fleeting, moving between objects and interaction, mothers tend to reduce bids for attention to novel objects and instead engage in extending the time spent on a particular toy or activity. *Opening* attentive engagements leads to a dispersal of sensorimotor schemes and is followed by *refocusing* attention on single objects. As a result of this, infants at about 12 months are able to handle objects with more elaborate schemes (e.g., bimanual coordination) and in patterns that are coherent with the interaction (taking turns, showing objects in response to an utterance, etc.).

The network metaphor serves to illustrate this process (Fig. 3). The infant's repertoire moves from a cluster of a few strongly interconnected schemes to a dispersal into differentiated forms of engaging objects and interacting, and then to the consolidation of equilibrated relations within and between these new skills. What this depiction does not show, however, is the systematic disequilibrium that is contextually induced by the adult, first in inducing a breakdown of excessive synergy, then in

refocusing excessive dispersal. Social encounters are more than sources of information. Even the metaphor of *scaffolding* is inadequate in that there is no doubt that caregivers do more than facilitate developmental change. They actively create the need for this change to occur in the first place and guide sensorimotor and interactive mastery in the infant in directions that are themselves embedded in complex historical and cultural patterns. This is clearly seen in concrete situations such as conversations during nappy changing (Rohlfing & Nomikou, 2014) or book sharing (Rossmanith, Costall, Reichelt, López, & Reddy, 2014).

These cases help us appreciate what a difference a world-involving perspective can make. Processes of different orders of magnitude and timescale (neural activity, enactments, social interactions, changes in sensorimotor repertoires, cultural practices, socialization into language, cultural change, etc.) are all *concurrently active* and mutually interpenetrate. The complexity of such situations is compounded when we notice that developing as a parent is a *co-occurring process* and adults are changed and disequilibrated by the infant's actions and emotional episodes, by worries about being a good parent, injunctions that they have absorbed from role models or have been imposed by social expectations, and so on (Di Paolo et al., 2018). Human sensorimotor repertoires *co*-develop. Differences in timescales serve to differentiate between all of these processes only to an extent. Ideas like autonomy can help us postulate the relevant logic of individuation and normativity in these multiple dimensions of concurrent change. But such distinctions only go so far. It is crucial for a process epistemology not to lose sight of the (often conflictive) convergence of determinations that takes place in the here and now of a concrete situation, such as a parent and an infant playing together, sharing a book, changing nappies. To treat such cases as having a bounded set of norms and influences may in general be sufficient for practical purposes. But it is misleading from a conceptual perspective and induces false divisions between processes that, for historical reasons, have been studied separately even when, in concrete cases, they are always happening together, all at once, and affecting each other. Interaction patterns and sensorimotor development mutually constrain, specify, and drive each other. The same happens between family routines and interaction patterns, between socioeconomic situation and family routines, between systemic patterns of oppression and socioeconomic situation, between instituted modes of production and systemic patterns of oppression, and so on. Sharing play time, having energy, attention, toys or books, or even the idea of sharing a book with an infant is not something all parents have access to or are able to do as freely as they would wish.

The complexity of human development can be daunting, especially when factors like the ones just mentioned are properly seen as processes, with their intrinsic dynamics, their intricate relations and multiple feedback loops. A proper study of development would seem to necessitate the joint efforts of various research disciplines, with the risk of a proliferation of well-justified but disjointed narratives that depend on particular perspectives. Attempting to unify complex phenomena under a single explanatory framework, on the other hand, runs the risk of abstraction and reductionism. Enactive ideas can be helpful because they develop dialectically rather than cumulatively. They try to capture increasingly concrete wholes in all their complexity (Di Paolo et al., 2018). The explanatory aim is to offer sufficient links so that enactive concepts can be useful for different investigations, from the relations between neurophysiological and behavioral processes, to social participation and so-

ciomaterial influences on agency. The precarious self-individuation of a network of sensorimotor schemes via equilibration dynamics is an example of such an open concept. On the one hand, it is subject to constraints of dynamical operationalization and, on the other, open to investigation in coupling with different kinds of processes at many scales. Each particular investigation renders this enactive idea increasingly more concrete, richer in refinements, and subject to revision. An enactive, process-relational approach to human development is therefore placed in a good position for questioning complex patterns between multiple timescales and orders of magnitude without erasing the concrete peculiarities of each phenomenal domain.

Conclusion

We are living through a difficult but exciting period in the sciences of the mind. Like clusters establishing new links, there seems to be a convergence between previously disconnected conversations and a potential for new flows. This situation, if we follow the foregoing discussion, could very well signal a new critical transition, with multiple potentialities for qualitative jumps in understanding, bringing together research practices historically separated by the demands of specialization but pursuing similar goals.

Offering an enactive account of sensorimotor agency, as hinted at above (see Di Paolo et al., 2017, 2018, for further details and discussion), hopefully opens avenues for further exchange, not only in terms of convergences, but also through unresolved tensions and questions that deserve further work. We can easily identify a few open issues that remain in need of examination and empirical scrutiny. One question that was merely hinted at is that of the circular influences between agency and development. Our account has not focused on the question of how actions, choices – in short, the active regulations that agents produce – affect developmental pathways and trajectories. This is in part related to the question of the development of reflective capabilities that allow agents to critically question concrete constraints on action and the need, or possibility, to overcome them. This is the question of how an agent's *powers* and *sensitivities* develop, of how agents may or may not be capable of critical attitudes and self-assertion. Such issues demand explanations using the world-involving perspective we have defended, where social encounters and sociomaterial environments play *more* than contextual or informational roles. They are beyond the reach of an individualistic approach.

One specific open technical issue to further this goal would be to apply the dynamical operationalization of sensorimotor equilibration to the study of *codeveloping* sensorimotor repertoires involving sustained adult-child and peer social encounters. Some suggestions are presented in the recent extension of enactive theory to language (Di Paolo et al., 2018). For instance, during participatory sense-making there are qualitatively different modes in which sensorimotor schemes in two or more people can couple, forming the partial components of a social act (like a handshake or the act of giving/receiving an object; Di Paolo et al., 2018, p. 148). But the details remain in need of further investigation. Interesting hints for such an investigation can be found in Piaget's own work on social equilibration in the case of qualitative value exchanges (Piaget, 1965/1995). Empirical studies also afford a rich opportunity for theorizing about peer-

driven codevelopmental change (e.g., Perret-Clermont, 1980). Another avenue, more explicitly explored in Di Paolo et al. (2018) following the work of Vygotsky, is the progressive attainment of socially mediated reflective powers and sensitivities following dialectical phases of alienation and self-actualization by which sociocultural practices first disrupt and later become appropriated by developing bodies. This goal could contribute to the ongoing task of overcoming the widespread individualistic biases (mainly in academia, perhaps less prevalent in therapeutic practices) in understanding cases of systematic developmental difference, which can nevertheless lead to complete forms of agency and worlds of meaning, e.g., in autism (De Jaegher, 2013; Di Paolo et al., 2018).

A process ontology should help us exorcize not only dualism, but also individualism. The rejection of individualism by enactivists might look paradoxical for a perspective so much invested in putting the questions of bodily individuation and meaning at the center of its outlook. But I hope the foregoing makes it clear that the opposite is the case precisely because in making individuality and agency questions in need of explanation we do not take them as explanatory axioms either explicitly or by default. Enactive explanations attempt to track the changing types of processual relations (contextual, enabling, constitutive) and the transactions between actual states and virtual conditions that underlie the normativity of sense-making. They do so, moreover, by adopting a world-involving stance, one that is demanded by the enactive conception of the dimensions of bodily self-individuation. The world, therefore, is not a mere source of information but an active participant in how bodies come to exist, develop, relate, and die. Bodies, together, change the world in turn. World involvement and the enacting of meaning in the human case are constitutively social. Our research is itself situated in the concreteness of our sociomaterial conditions. These multiple epistemic loops are initiated by putting meaning and agency back at the center of cognitive science and psychology, and by adopting a world-involving perspective and dynamical systems tools for modelling and operationalizing new ideas. But the loops do not stop there; the ideas remain open to further concretization and change as communities of knowledge themselves change.

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