Acting up: An approach to the study of cognitive development

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4

Acting Up

An Approach to the Study of Cognitive Development

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Im Anfang war die Tat. [In the beginning was the deed.]
—Goethe: Faust

Abstract

Despite decades of research, we lack a comprehensive framework to study and explain cognitive development. The emerging "paradigm" of action-based cognition implies that cognitive development is an *active* rather than a passive, automatic, and self-paced maturational process. Importantly, "active" refers to both sensorimotor activity (in the narrow sense) as well as to autonomous exploration (e.g., as found in active perception or active learning). How does this emphasis on action affect our understanding of cognitive development? Can an action-based approach provide a much-needed integrative theory of cognitive development?

This chapter reviews key factors that influence development (including sensorimotor skills as well as genetic, social, and cultural factors) and their associated brain mechanisms. Discussion focuses on how these factors can be incorporated into a comprehensive action-based framework. Challenges are highlighted for future research (e.g., problems associated with explaining higher-level cognitive abilities and devising novel experimental methodologies). Although still in its infancy, an *action-based approach to cognitive development* holds promise to improve scientific understanding of cognitive development and to impact education and technology.

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Introduction

During their first years of life, children greatly increase their action repertoire to acquire sophisticated cognitive and interactional abilities (e.g., conceptual, inferential, and linguistic). How this is accomplished has been the focus of much research. To date, however, we lack a comprehensive scientific framework capable of explaining cognitive development and the relations (if any) between action and cognitive development.

In traditional cognitive science, "action" and "cognition" are often studied in isolation, with the role of action reduced primarily to the execution of a motor response. New, promising action-based theories emphasize, however, that it is only through action that a living organism can "know" or "cognize" its environment; thus action must be considered integral to cognitive processing (Engel et al. 2013; Pezzulo et al. 2011; Pezzulo 2011; Thelen and Smith 1996). How does an emphasis on action affect our understanding of cognitive development?

An action-oriented perspective views cognitive development as an *active* process rather than one that depends solely on automatic, self-paced maturational processes. More specifically, if children are to discover (and learn to predict) increasingly complex and profound regularities in their bodies and the external world, they must engage *actively* with their physical-social environment. This engagement, in turn, forms the basis for increasingly sophisticated action and cognitive abilities.

The dependence of perception and cognitive processing on action has been captured nicely through the sensorimotor contingency (SMC) theory (O'Regan and Noë 2001). Accordingly, the cognitive processing of a child (or, more generally, a living organism) does not originate from a *stimulus* but rather from an *action* (and usually an *intention*). By acting, a child causes regularities in sensorimotor patterns, which are then successively experienced. This permits a child to master the regularities in perception-action patterns, or SMCs. Although SMC theory has been used primarily to study perception, the mastery of SMCs could be considered crucial for the development of both action and cognition. This mastery guides an individual's own actions toward goals (intentional action) and permits a person to predict the consequences of the action (anticipation). It also permits an individual to produce sensory stimuli that are maximally informative; that is, to recognize an agent or object (perception and discrimination) and to learn its characteristics over time (learning and memory). Since actions are usually performed in social domains, actions also afford social communication and signaling, which create new opportunities for social and cultural learning. In sum, SMC theory emphasizes the tight link between perception and action systems and the importance of active, exploratory activities on cognitive development.

It is important to emphasize that the word "active" refers not only to sensorimotor action but also to exploration (as in active perception or active

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learning). Furthermore, although an action-oriented view of cognitive development gives prominence to active exploration and engagement with the environment, it does not dismiss other factors that do not appear to be linked to action, such as the importance of genetic regulation or sociocultural factors, which are likely to produce "biases" to action-based processes (e.g., by focusing our attention on important novel events or on actions performed by our conspecifics). Viewing cognitive development from an action-oriented perspective holds the promise of providing a comprehensive framework—one capable of contextualizing all factors important to cognitive development. Similarly, an action-oriented approach targets the whole range of phenomena used typically to explain development theories (e.g., the acquisition of conceptual, inferential and linguistic abilities); it is not confined to a portion that seems more closely related to sensorimotor action. We propose that research should focus on how all these (and other) abilities depend on, or at least link to, action—directly or indirectly. The research program that we envision and discuss is in some aspects new, but it connects well with existing theories of cognitive development.

Factors and Mechanisms Influencing Developmental Processes

The importance of action for cognitive development has long been recognized by "behaviorists" (Thorndike 1932; Skinner 1938) and "constructivists" (e.g., Piaget 1952) as well as recently by others (Thelen et al. 2001; von Hofsten 2004). However, the specific mechanisms and factors that underlie action-based cognitive development await detailed identification.

Since an action-oriented approach emphasizes the importance of sensorimotor learning, it is natural to assume that the most important candidates for cognitive development would be those that underlie intentional action control. Contemporary theories of action control highlight the importance of internal models (e.g., forward or inverse models) and associated "efference copies" or "corollary discharges" of motor control signals as basic mechanisms of sensory processing, prediction, and motor control (Adams, Shipp et al. 2013; Blakemore et al. 2001; Crapse and Sommer 2008; Grush 2004; Shadmehr et al. 2010). These mechanisms may also be crucial for cognitive development and it has been suggested that a copy of the efferent motor command rerouted to the sensory pathway is necessary for organisms to differentiate between reafference and exafference, so that the organism can distinguish the source of sensory inputs; that is, whether an input results from the organism's own (spontaneous) movement or emanates from the environment (von Holst and Mittelstaedt 1950). During the early stages of life, this process immediately creates a feedback loop through which both sensory and motor information are connected, thus forming the basis for sensorimotor learning and potentially providing a way to distinguish self-movements from other movements. It has

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also been suggested that predictive (forward) models implied in motor control might be key for the acquisition of cognitive and social abilities: they might permit cognitive agents to understand objects in the environment as well as the actions of other agents, in terms of anticipated sensorimotor patterns, thus permitting the acquisition of various interactive abilities such as coordination and action prediction (Jeannerod 2006; Pezzulo and Dindo 2011; Pickering and Garrod 2013b; Sebanz and Knoblich 2009). Forward models might also support exploratory strategies (e.g., hypothesis testing) for perceptual processing, belief revision, and skill learning (Friston, Adams et al. 2012; Gottlieb et al. 2013).

Despite their importance, mechanisms which directly link to sensorimotor learning do not offer a sufficient explanation to construct a comprehensive action-based theory of cognitive development. Traditional theories of development have proposed several potential causal factors: genes, social and cultural factors, emotions, experience, etc. An action-based approach to cognitive development needs to integrate most or all of these causal factors and recast them on the basis of their contribution to action-based processes. Below we review some of the most important factors to be considered in such an ambitious synthesis.

Common Paths of Development and the Action-Experience-Sociality Triad

Models that emphasize the role of action in cognition, or claim that cognition is action, tend to emphasize the role of experience (and especially social interaction) rather than that of genetic factors in development. Why is this? One explanation may be found in the historical treatment of action and experience (e.g., pragmatism and behaviorism). Alternatively, action and experience may be seen as the joint product of a more encompassing view of organisms as agents: makers rather than takers of their fate.[1]

However, even the link between empiricism-about-action and sociality might contain a strong element of necessity, which might reveal common paths of development despite the vast differences in individual experiences. The development of cognition needs guidance from somewhere, and if that guidance is not genetically driven, it may come from the social world. The constraints provided by the physical environment—the brute properties of objects—are insufficient, although they could be complemented by social aspects (e.g., caregivers, or co-actors more generally, often support the learning process by providing a pedagogical context) (Csibra and Gergely 2011; Pezzulo, this volume). Furthermore, members of each culture want their children to grow up performing actions in distinctive ways. The cultural specificity of action serves to

[1] A focus on organisms as "makers of their fate" has further impact on the understanding of autonomy and responsibility, thus opening various ethical and social questions (Nagel 2010).

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enable the cumulative cultural inheritance of skills (Tomasello 2014), thus providing a source of shibboleths, or "ethnic markers," to identify who is eligible for reciprocal altruism (Cohen 2012; Hamlin et al. 2013; Riečanskỳ et al. 2014).

Hamilton et al. (this volume) point out that some motor skills show a highly protracted developmental trajectory (e.g., grip aperture, scaling, grip force, end-state comfort). In such cases, later stages of skill acquisition might represent adjustments to cultural norms rather than to the raw physical requirements of the motor tasks. Identifying the role of cultural influences on cognitive development and their potential adaptive value (e.g., as in the proposal of "ethnic markers") is an important direction for future research.

Identifying Biases and Constraints in Action-Oriented Processing and Development

A related, important issue involves the identification of various "biases" that guide and shape development (e.g., by constraining the space of sensorimotor learning and the acquisition of SMCs). There is a danger of assuming that if we correctly understand only the earliest and most basic processes and learning mechanisms (e.g., associative mechanisms), then the rest of development will magically emerge. A more comprehensive view needs to consider that experience-dependent learning is constrained and that not all SMCs are learned with equal ease. For example, it is very easy for monkeys to learn to fear a snake by watching on video the response of a model that is afraid of a snake; however, it is almost impossible to learn fear of a flower, even if the video is identical (substituting the flower for the snake) (Mineka and Cook 1993).

One example of anatomical and physiological constraints to experience-dependent learning is the brain's division into ventral and dorsal streams: the ventral stream is dedicated to the "what" (i.e., object) and the dorsal stream to the "where" (place). This division constrains what can be acquired during development (Milner and Goodale 2008). Another example of bias in development is the presence of reflexes that guide the initial exploration and shaping of the SMCs to be learned (Verschure et al. 2003).

It is important to consider what the anatomical requirements of associative learning systems are that putatively support the acquisition of SMCs. One such requirement is that the relevant sensory and motor domains must be connected to each other, thus providing the basis for associative linkage. This argument is important, for example, in the domain of language. Macaques do not have a strong dorsal connection between auditory and motor systems in their brains, whereas humans have such a data highway for auditory-motor association: the arcuate fascicle. Associative learning of speech may critically depend on the availability of ample connectivity in this domain-specific auditory-motor system (Pulvermüller and Fadiga 2010).

We still lack a systematic taxonomy and understanding of the various biases that constrain action-oriented processes and guide cognitive development.

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These biases might be very diverse, emphasizing once again the necessity of an integrative research program. To exemplify the diversity of the possible biases, we review two classes: genetic factors and the mechanisms that drive autonomous learning and exploration.

Genetic Influences on the Learning of SMCs and Cognitive Development

Almost every account of development recognizes that there are contributions from genetics, learning, and social interaction. Thus, it should not seem odd to highlight the importance of genetic processes within an action-based approach. Nevertheless, most action-oriented approaches emphasize the contributions of learning over those of genetic inheritance and suggest that the genetically inherited components are quantitative biases rather than whole, dedicated cognitive processes. They also stress the action-related aspect of these genetically inherited biases.

The idea that genetics can exert important influences on development should not, however, be sidestepped. Genetics has often been identified with fixed, inflexible, and phylogenetic traits and plasticity with nongenetic processes. As a consequence, human action and the development of cognition were held to be too flexible to be contextualized in a molecular perspective. We now have the tools to revise this picture. There is every reason to assume that innate mechanisms, honed by millions of years of evolution, are not fixed and rigid behavior programs but rather pre-prepared "startup kits" which lead not only to flexible behavior but may also reveal individual differences (Carey and Gelman 2014; U. Frith 2012).

To understand better how evolution and genetics can play a role in development, it is important to note that nature ultimately influences, through natural selection, the *phenotype* (bodily patterns of both morphology and behavior) and not the micromorphology (including neural circuitry and its operating mechanisms), which realizes behavior. Accordingly, genetics and neural mechanisms are instrumental to support adaptive phenotypes. In turn, actions (behavioral phenotypes) are constrained by bodily structure, neural control mechanisms, and learning processes (including social learning), all of which interact dynamically, thus making a complete genetic specification unlikely (Edelman 1987). Certain important constraining factors to development are more likely to be encoded genetically. The human face preference in neonates is a good example (Johnson et al. 1991): From birth, human infants "track" the movement of a face-like stimulus (a triangle of dark blobs on a light background, with two blobs at the top) longer than a control stimulus (a similar triangle but with two blobs at the bottom). This bias makes the infant highly receptive to information from other people. In addition, this bias is action oriented in that it involves "tracking" (i.e., moving the head to keep the stimulus in view, which itself is a moving target). As this example clearly illustrates, the action oriented research

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program should not dismiss the importance of genetic factors but rather clearly identify their synergistic impact on action-based processes.

Mechanisms That Drive Autonomous Learning and Active Exploration

Another class of constraints involves mechanisms that support autonomous learning and active exploration. To acquire mastery of SMCs, children face several challenges: First, the sensorimotor spaces to be modeled are high-dimensional and nonlinear. Second, different from most machine learning algorithms (used, e.g., by web companies to classify texts or images), infants do not have access to preconstructed databases containing millions of learning examples. Instead, they have to learn incrementally through physical interaction and by performing sensorimotor "experiments," which carry costs in time and energy. Which learning and exploration methods should children use to solve the formidable challenge of SMC learning? This question can be approached based on contributions from both computational neuroscience and robotics research.

We need to understand which types of learning mechanisms can derive regularities from these data. Recent advances in theoretical neuroscience suggest that different (e.g., perceptual and structural) learning mechanisms might interact and operate on different timescales (Friston, Daunizeau et al. 2010). Furthermore, computational models of cognitive development emphasize that the developmental process needs some guidance from so-called "inductive biases" that pre-shape the space of what can be learned (Tenenbaum et al. 2006). Understanding how different learning processes and biases might interact synergistically requires the development of integrated architectures, possibly embedded in physical robots that operate in realistic sensorimotor contexts—all important open problems at the forefront of computational modeling and robotic research (Friston 2010; Verschure et al. 2014).

We also need to understand which mechanisms *guide* exploration to collect informative and useful data. Action-based theories emphasize how important it is for children to explore their environment actively and test their hypotheses—an idea which links well with the view of the "child as scientist" (Gopnik and Schulz 2004). Indeed, learning theory and models in developmental robotics show that collecting data through randomly chosen experiments is bound to fail and that constraints are needed (Oudeyer et al. 2013). It is also important to consider the fact that not all SMCs in the world are identifiable and learnable by organisms, due to limitations in time, energy, computational or inferential resources. Some contingencies may also become learnable only after certain prerequisites have been acquired. Thus, exploration strategies should include mechanisms which focus sensorimotor experimentation on those subspaces/activities that are currently "learnable," given the cognitive agent's prior knowledge and skills. These map onto what Vygotsky (1978) called the "zone of proximal development."

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Current research in developmental robotics has helped elucidate several families of (interacting) mechanisms that guide and constrain exploration. This includes the biomechanical and physiological properties of the growing body, with developing neural synergies and perceptuo-motor systems. Another family of such guiding mechanisms is social shaping of the learning environment, which drives the attention and activity of learners through a diversity of social strategies (e.g., imitation, emulation, teaching strategies). Finally, *motivational* mechanisms are key in driving the organism to select particular actions and particular sensorimotor experiments. It is important not to limit research to *extrinsic* motivational systems, where the organism is driven to search for things like food or social bonding, but to include *intrinsic* motivational systems, where the organism's brain assigns value to information gain or competence gain, leading to spontaneous exploration (Baranes et al. 2014; Mirolli and Baldassarre 2013). Such intrinsic motivational mechanisms can be viewed as proximal mechanisms which favor curiosity-driven and novelty-seeking behavior as well as, ultimately, the acquisition of good predictive models for adaptive action. In developmental robotics, the development of an integrated approach to the modeling of these families of "guidance mechanisms" for exploration and their interactions is a challenge that has not yet been met.

Open Issues: Studying Development as a Continuous yet Nonhomogeneous Process

How do all the factors identified thus far operate and interact over time? The view, illustrated in Figure 4.1, is that *development is a continuous yet nonhomogeneous process* that might proceed at a different pace at different periods, where different mechanisms, genetic, associative and cultural (or their combinations) might play a more prominent role.

During the early (fetal and neonatal) stages, movement triggered by endogenous input (including intrinsic motivation) orients an individual's initial movements, thus creating the primitive establishment of SMCs. During these phases, the ways in which an organism interacts with its environment are constrained, and we can talk of a maturation of SMCs or their prerequisites, such as an initial development of basic motor abilities. In the postnatal period, maturation and a more sophisticated learning of SMCs (e.g., based on associative mechanism) overlap and interact, and infants enter into new phases of cognitive development which last quite a long time (Hilgard 1991; von Hofsten 2004). Different factors (from molecular regulation to social interactions) become extremely important; in addition, brain plasticity plays a crucial role in correlating cognitive development to the external context in a way that is not predetermined. During later phases, SMC learning becomes increasingly powerful: generalization becomes possible, capitalizing on the fact that children have increasingly more sophisticated experiences. For example, when children learn to stand still, they also learn to recognize and manipulate

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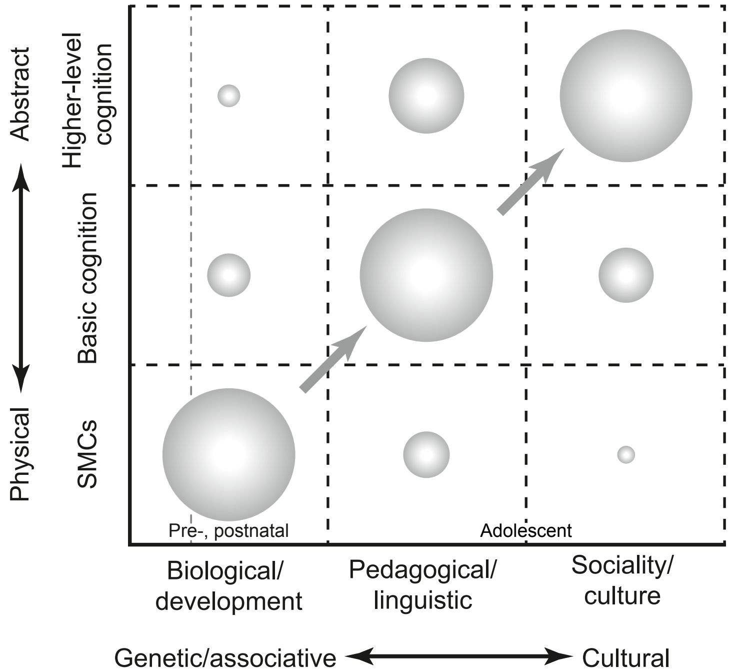

Figure 4.1 Development of physical and cognitive abilities is shaped by various genetic, associative, and cultural factors whose relative importance changes over time. The size of the dots represents the relative importance of the various factors during developmental time: from pre- and postnatal periods, when the primitive SMCs are established (bottom left), to later phases (e.g., adolescence), when social and cultural factors become dominant in the development of higher cognitive skills (top right).

a greater number of objects, and they interact in richer ways with their caregivers. Successively, children are exposed to increasingly richer contexts (social, linguistic, and pedagogical), which reach a high level of complexity in adolescence.

Essential "phase transitions" may exist in the developmental process and might be induced, for example, through the growth of the brain and the increasing complexity of social interactions supported by language development (following the maxim that "more is different"). Some of these phase transitions might reflect qualitatively different and discontinuous characteristics of higher abstraction and concept formation, perhaps powered by linguistic "start-up kits," where concept formation and the simultaneously developing language skills shape one another in a virtuous circle. From this perspective, the property that emerges from the phase transition would be qualitatively different yet physically based on existing systems. The massive and rapid expansion of the human brain during the recent evolution of hominids would contribute to the emergence of so-called human-specific higher cognitive functions (Iriki and Taoka 2012). Further research is needed to provide empirical support for these initial hypotheses as well as to link phase transitions and the classical concept of "stages" in cognitive development (Piaget 1952).

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The motivation to learn new skills has roots in social cognition and imitation of valued adults or peers. Learning context, in no small measure, guides the onset of learning, the form the practice takes, and the pleasure the learner is experiencing in mastery. This example emphasizes the gap in current research: we need to identify a link between sensorimotor and motivational, intentional, and cultural goal processes in development. Some aspects of this have been studied within the tradition of associative learning theory (Balleine and Dickinson 1998; Klossek et al. 2008). However, this research, and other theoretical and empirical resources from the same tradition, could be productively integrated with research that is more obviously part of an action-oriented and culturally/socially embedded approach to cognitive development.

The Development of Higher Cognition

Action-oriented theories seem particularly well suited to explain the development of simple cognitive abilities which have externally perceivable or manipulatable objects as referents (e.g., the categorization of objects) (Chao and Martin 2000). A crucial challenge for action-oriented approaches is to explain the development of higher cognitive abilities at large, including our linguistic abilities, capacity to use abstract concepts, and cognitive operations such as planning, reasoning, and the engagement in social exchanges.

The action-based perspective of cognitive development diverges from other more classical approaches in suggesting that linguistic and conceptual knowledge acquired during development is grounded in perceptual and motor systems rather than being a symbolic modular system or an "encyclopedia" of concepts unrelated to action and perception systems (Barsalou 1999). This applies to domains traditionally considered to be symbolic (e.g., language) as well as to abstract concepts (e.g., "truth" or "democracy"). How is this possible? Below we highlight several required steps toward an action-oriented account of abstract concepts and their development, which ultimately point to the necessity of a broad notion of action-oriented processing.

Toward an Operational Definition of "Concept" That Is Not Too Restrictive

A first important step toward the specification of action-oriented theories of concepts is methodological: we must define a minimal constraint for the use of the notion of "concept." In several disciplines (e.g., philosophy or psychology), possessing a "concept" means more than just possessing discrimination abilities. Discriminations do not necessarily require cognitive abilities: a red detector is able to discriminate reliably between "red situations" and "non-red situations." In contrast, we usually explain more complex abilities with the possession of concepts. Consider, for example, the concept "red." Possession

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of the concept requires more than discriminatory abilities; one must be able to group together objects with other colors but not, for example, shapes (for an ability-based account of concepts, see Newen and Bartels 2007). The possession of the concept "tool" might be related to the action possibilities it affords (Chao and Martin 2000; Maravita and Iriki 2004), a characteristic that is especially relevant from an action-oriented point of view. Thus, one desideratum for future empirical research would be to identify the specific action possibilities a specific concept offers and to test for the presence of such actions instead of only testing discriminatory behavior. This seems to be most relevant for "abstract" concepts. The possession of the concept of *democracy*, for example, does not only lead to the ability to discriminate between democracies and non-democracies. It relates to a number of different practical skills: from voting and taking part in fair discussions to representing others in the community or accepting opinions different from one's own.

Abstract Concepts and Their Relation to Language, Interoceptive Systems, and Sociality

Explaining abstract concepts is a key benchmark for action-based theories of cognitive development, because they seem prima facie to be not particularly related to action (at least in the restricted sense of sensorimotor action). It is generally assumed that abstract concepts are linguistically coded (e.g., Paivio 2007), in line with physiological evidence of greater engagement of the left perisylvian language network for abstract rather than concrete words (Binder et al. 2009). Moreover, it has been argued that abstract words are learned by extracting distributional or syntactic information from sentences in which these words are used (Gleitman et al. 2005). Accordingly, linguistic (especially syntactic) development is taken to be a prerequisite for the learning of abstract concepts.

Contrary to the hypothesis of a separate cognitive domain for abstract and linguistic processing, there have been various attempts to characterize the acquisition of abstract concepts as intrinsically action and interaction related. Below we summarize proposals which highlight the importance of affective or interoceptive processing, mental operations, and social dynamics.

Based on recent behavioral and imaging work, which used tighter matching of items than previous studies, some argue that abstract concepts entail affective processing to a greater extent than concrete concepts (Kousta et al. 2011) and, for this reason, that their encoding comprises neural networks engaged in processing emotional stimuli (Vigliocco, Kousta et al. 2014). There is a statistical preponderance of affective associations underlying abstract word meanings. According to Kousta et al. (2011), our internal affective experience, linked to interoceptive responses, would provide at least grounding at an early stage to abstract concepts: words that denote emotional states, moods, or feelings could provide examples of how a word may refer to an entity that is not

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externally observable but resides within the organism. Consistent with this possibility, abstract words that denote emotional states are the first abstract words to emerge during language development (e.g., Wellman et al. 1995). Such an early bootstrapping of abstract words from emotion could rely on interoception as well as on action, since several emotions are expressed in actions and these actions can be linked to words (Moseley et al. 2012).

Affective and interoceptive states are not the only "internal" referent for abstract concepts. Barsalou (1999) proposed that concepts such as "truth" might be grounded in internal cognitive operations (e.g., the "matching" of an expected and a perceived situation). How such internal operations could be linked to SMCs remains a challenge.

Another set of action-based theories of abstract concepts highlights the *social* nature of the concept and word-learning process. In the case of concrete entities, Borghi and Binkofski (2014) argue that the presence of a given object (the referent of the concept or word) constrains our sensorimotor experience, whereas in the case of abstract entities, concepts are grounded in interpersonal sensorimotor and situational experience. This different "modality of acquisition" might distinguish how concrete and abstract concepts are learned and represented. Related to this, Pulvermüller (this volume) suggests that the acquisition of SMCs can be relevant for both concrete and abstract semantics, but that these would differ significantly due to the different correlation structure of referent objects of concrete and abstract terms (e.g., "eye" versus "beauty") (see Figure 9.1 in Pulvermüller, this volume). All of these proposals for an action-based foundation of conceptual processing remain to be assessed in future studies.

A Specific Example of an Abstract Concept: The Case of Morality

Emotional and social action-based processes have been implicated in the development of moral sensitivity. Over the past ten years, there has been an upsurge of empirical research into moral cognition and the evolutionary function of the human moral sense (or faculty). One proposal is that the evolutionary basis of moral cognition is the pressure generated by the need for cooperation among humans. Baumard et al. (2013), for example, argue that human moral sense evolved within a market of cooperating partners: an agent's moral behavior serves to increase his or her reputation as a cooperative partner.

We can readily imagine that moral sensitivity is based on action contingencies and affective processes that relate to reward and punishment, when outcomes of moral actions have to be judged. A central concept that has been suggested to underpin the development of morality is *doing or not doing harm*. Even eight-month-old infants prefer agents who act positively toward prosocial individuals as well as agents who act negatively (punish) toward antisocial individuals (Hamlin et al. 2011).

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A highly relevant concept to the judgment of moral behavior is whether the behavior was intended or accidental. *Intentionality* is a (possibly uniquely human) capacity with a known neural signature that underpins the ability known as "mentalizing" (Frith and Frith 2012). This ability, among other things, allows us to classify actions as deliberate or accidental. Studies using fMRI in adults have shown that the mentalizing network, which includes the right temporal-parietal junction and medial prefrontal cortex, is active when moral judgments are being made (Koster-Hale et al. 2013).

The adult conception of moral judgment tends to give primary importance to an agent's intention when action is evaluated; however, the importance of the outcome of an immoral act should not be overlooked. Preschool children give a lot of importance to the outcome. Thus, they judge agents who cause accidental harm far more harshly than agents who intended but failed to harm another person. Preschool children are perfectly able to understand the content of others' intentions, so why don't they make use of this information in their moral evaluation? One possible explanation comes from an experiment by Buon et al. (2013), who showed children nonverbal cartoons depicting three conditions: (a) an agent intentionally causes harm to his victim; (b) an agent accidentally causes harm to his victim; (c) an agent is present when another gets hurt, purely by coincidence. Their results showed that five- and three-year-olds' moral evaluations were more sensitive to the agent's "causal" role than to the agent's "intentional" role. Interestingly, the same was true for adults when they had to make moral judgments under cognitive load (Buon et al. 2013).

Studies by Koster-Hale et al. (2013) provide further evidence that, in adults, it is cognitively easier to blame agents of attempted harm (who intended, but failed to cause harm) than it is to exculpate agents who caused accidental harm. As expected from the fMRI results in this study, ventromedial prefrontal cortex patients failed to condemn attempted harm because they failed to experience any emotional aversion when they retrieved the content of the agent's malevolent intention (Young et al. 2010). However, individuals with autism spectrum disorder, who have difficulty attributing intentions, failed to make use of the information about the content of the agent's false belief to exculpate the agent who caused accidental harm without any malicious intention (Moran et al. 2011).

This example demonstrates the high-level concepts that are part and parcel of cognitive development and which are amenable to being explained in terms of action-based theories. Like many other "abstract" concepts, moral concepts may include both "individualist" elements (e.g., interoceptive and affective codes) and "social" or "collective" elements; that is, moral judgments can involve actions performed by others and their outcomes. This suggests the necessity of a broad action-oriented view—one that goes beyond the restricted domain of an individual's own sensorimotor control mechanisms. It also suggests that the current focus of action-based theories on simple forms of sensorimotor control should be expanded toward richer theories that include

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executive control. Indeed, the adult accomplishment here and in many other capacities is strongly influenced by effortful inhibitory mechanisms that serve to facilitate interaction and cooperation, and it thus should be included in action-oriented analyses.

Sociocultural Factors in Concept Learning: The Case of Supernatural Beliefs

Our discussion of the case of morality has highlighted the complexity of the relationship between concepts or beliefs and sensorimotor representations. Another domain where this is apparent concerns abstract supernatural beliefs. The Ifaluk of Micronesia, for example, believe that if a person is feeling sad, this will cause their relatives on a different island to become ill (Lillard 1998; Lutz 1985). In this example, it is likely that a belief has no physical or sensorimotor basis but is rather acquired and maintained via social-cultural mechanisms. Nonetheless, this belief may well have sensorimotor consequences, as demonstrated by the following: a person who believes their relative's illness is caused by events on another island might not provide the same medicines to a sick person as someone who believes that illness originates physiologically. Linking abstract beliefs to consequences, however, does not always work. Sperber (1975:33) reports that the Dorze in Ethiopia regard the leopard as a Christian animal—one that does not eat meat on Fridays. This belief could lead villagers to decide that their livestock are safe from predation on Fridays, yet they secure their chickens on Fridays, just as they do every other day. This example shows how an abstract cultural belief does not relate to the actions people actually perform, even though the belief still remains embedded in that culture. Together, both cases provide examples of knowledge or beliefs that are hard to connect to sensorimotor experience alone. They point instead to a critical *sociocultural* mode of acquiring knowledge.

If we address the question of how abstract concepts (e.g., democracy or morality) are learned by thinking only about individual minds, we run the risk of underestimating the complexity of some abstract concepts or of postulating very weak "grounding" relations to SMCs to bridge the gap. These risks can be averted if we recognize that such abstract concepts are produced by large groups of minds, over many generations, as a result of cultural evolution. In the course of ontogeny, individuals do not need to create these concepts, they only need to adopt them. This is far from being a trivial task: other agents supply not only the conceptual content, they assist individuals in adopting them and support the adoption process through scaffolding and explicit instruction. Where is the influence, then, of SMC learning? At the very least, SMC learning influences the construction of mechanisms that enable the child to learn from others (e.g., caregivers), via observation and instruction (Heyes 2012), and it gives the child a "database" of empirical regularities to be explained by abstract concepts.

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Sensorimotor Learning Can Provide a "Database" for Learning and Development

Action-oriented approaches emphasize the importance of sensorimotor learning. There is a consensus that this type of learning is important in the early stages of cognitive development, but there is considerable disagreement about the role that sensorimotor learning plays in the development of "higher" cognition (e.g., in the development of mentalizing). One view is that action understanding and #mind-reading abilities are based directly on mechanisms that support action control (Rizzolatti and Craighero 2004). Another view, still consistent with a "weaker" version of the action-oriented approach, holds that the linkage between action and mentalizing abilities is more indirect. For example, sensorimotor learning enables infants to encode and predict regularities in the behavior of others: when a person begins to move a spoon of porridge from a bowl, the spoon is likely to end up in the person's mouth. Subsequently, children learn an explicit "theory of mind"[2] from adults and peers in their culture. An explicit theory of mind may be acquired through conversation and instruction, rather than through sensorimotor learning (Heyes and Frith 2014), but it allows the child to interpret the SMCs coded in their database. For example, the spoon is likely to end up in the agent's mouth because the child *wants* to eat porridge and *knows* that moving the spoon to her mouth will allow her to do this. Accordingly, sensorimotor learning provides a "database" which is then interpreted by cognitive processes acquired by a different route.

Abstract Cognitive Operations

An objective of action-based approaches is to determine whether and how cognitive operations such as reasoning, planning, and understanding others' intentions might reuse (or capitalize upon) the same action-and-prediction strategy that underlies the mastery of SMCs. Various researchers have proposed that the fundamental machinery supporting intentional action—including most prominently *internal forward models*—might be reused covertly "in simulation" of overt behavior (Jeannerod 2006). The same sensorimotor loops might be reenacted during planning and action understanding. Conceptual systems have been proposed to consist of "situated simulators" that permit reenactment and recombination of previously productive situations experienced; using such

[2] It might be useful to distinguish between an explicit and implicit theory of mind (also known as mentalizing). The development of the latter could be based on an innate start-up kit, which is proposed to be missing in autism (U. Frith 2012). Learning based on this start-up kit appears to be extremely fast: using eye-tracking techniques, Kovács et al. (2010) showed that seven-month-old infants are able to track an agent's belief. This mechanism for automatic tracking of beliefs (mentalizing) is still available to adults in parallel with explicit theory of mind. Although able autistic individuals (Asperger Syndrome) can acquire explicit mentalizing, they seem unable to acquire automatic mentalizing (Senju et al. 2009).

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"simulators," a modal conceptual system might support the entire range of complex cognitive operations traditionally associated with the manipulation of amodal symbols (Barsalou 2009; Pezzulo et al. 2011).

In parallel, a "weaker" version of action-based theories has emerged: complex cognitive operations use mechanisms analogous to those providing a mastery of SMC, but they involve other kinds of contingencies which are not strictly sensorimotor but are so-called "second order," in the sense that they partially or totally abstract from sensorimotor loops (for a discussion, see Pezzulo, this volume). Chess playing offers a specific example of operations that do not entail strictly SMCs but other, possibly higher-order contingencies, especially if appropriately subdivided into smaller steps. Thus, chess playing could be viewed as a movement-like situation: by planning ahead for the consequences of an action, the motor aspect would map to the specific movement of a piece whereas the sensory consequences would be the outcome of the action (i.e., how good or bad is the position of the piece) or the expected responses of the opponent. Accordingly, the specific movements executed by the hand to move a piece would be less relevant than the "movement" in a more abstract action space that is shaped by the rule of chess—hence the idea of higher-order contingencies.[3]

Open Problems

Explaining the development of abstract concepts and higher cognitive abilities is a key challenge for action-oriented views. We began this article by considering the centrality of sensorimotor skills and SMCs in cognitive development and have discussed several important factors (the importance of proprioceptive and affective states, language, and social dynamics) that should be integrated within a more comprehensive account of cognitive development. As the example of moral reasoning illustrates, all factors contribute to the advanced cognitive skills that make us humans, and—at least in principle—all can be reformulated and integrated within an action-based approach, providing that the approach is not too restrictive.

Our analysis, though, exposes important questions: What is preserved from the original concept of *sensorimotor contingencies* in domains of abstract

[3] This "second-order" approach to SMCs poses a potential problem for "strong" action-oriented or "enactive" views (for terminological clarifications, see Dominey et al., this volume). Imagine that to encode an SMC for future use, the cognitive system stores the conditional probability of the appearance of a certain sensory state given a certain motor command. The encoding of such a probability represents something about (or carries information about) the sensorimotor processing, without necessarily being in a sensorimotor code. Consider a discursive list of all of the paintings in the Louvre: the entries on the list are about images, but the list, as an encoding, need not itself be imagistic. An action-oriented theorist, who is only interested in grounding according to Harnad (1990), might gladly embrace such models. However, someone who thinks cognition is entirely action-constituted (or sensorimotor-constituted) might not be satisfied with this result.

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cognition: the sensorimotor format, the importance of seeing knowledge in terms of contingencies, both or neither? Do abstract concepts really "abstract" from sensorimotor experiences, in the sense of forming a schematized and potentially amodal internal representation, possibly linguistically mediated? Or should abstract concepts be conceptualized as "situated simulators" (Barsalou 2009) that reenact sensorimotor experiences, or even more drastically as collections of exemplars that share a family resemblance (e.g., for democracy, exemplars of situations where I vote, I discuss, etc.)?

More generally, once an abstract concept has been acquired, does it retain a "sensorimotor signature"? Consider two opposing, relatively extreme responses. The first fully reduces abstract concepts to encodings of SMCs: an abstract concept is nothing more than a set of such contingencies, properly grouped or associated together. The concept of a university, for example, can be formed of various associations between experiences of ways one might act (e.g., walking through a building) and the experiences that follow (e.g., the visual perceptions of classrooms and offices), to oversimplify the point. The second view takes SMCs to play a role only during the acquisition of abstract concepts: sensorimotor experience is like a ladder that gets kicked away once an abstract concept has been mastered. A subject might need some kind of sensorimotor experience to master the concept of a university (e.g., a subject must see some type of large institutional building or hear a lecture in one of them). Nevertheless, once a subject has had a sufficient amount of experience, the concept is mastered and the sensorimotor experiences that facilitated acquisition play no substantive role in the subject's later deployment of that concept. The subject can reason about and solve problems related to, for example, universities, without necessarily relying on any sensorimotor routines or engaging in any distinctively sensorimotor processing—thus using "amodal" concepts (Pezzulo, this volume; Weber and Vosgerau 2012).

These two views, however, do not exhaust the space of possibilities (Gentsch et al. 2016). Although an abstract concept may be used to solve problems, for example, in keeping with logical or semantic rules (e.g., universities enroll students, students read books, and so on), abstracted from sensorimotor processing, cognitive processing involving such units might reflect certain aspects of the way in which they were related to sensorimotor processing during acquisition. Sensorimotor aspects of concepts that generally appear to be amodal (as they are applied to a variety of circumstances) might be revealed through well-designed experimental manipulations in the manner of Chen and Bargh (1999). In their experiment, subjects were asked to recognize words with positive valence. They were able to do this more quickly when asked to indicate word recognition by pulling a lever toward themselves. Thus, it might be that after acquisition the neural unit which serves as the vehicle of the relatively amodal representation "*good stuff*" remains causally associated with the motor processing involved in the bodily action of pulling something toward oneself

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(Rupert 1998, 2001, 2009). Such concepts may be neither fully reducible to SMCs nor entirely abstract.

Brain Mechanisms Supporting a Mastery of SMCs and Cognitive Development

Thus far we have described various factors and mechanisms that underlie cognitive development and elucidated the centrality of SMCs in this process. We have also discussed how an action-oriented approach might explain the development of higher cognition. How, then, can this action-oriented view of cognitive development be realized in the neuraxis?

Action-Perception Loops in the Brain Permit Acquiring a Mastery of SMCs

Does the brain architecture in humans (as well as our early evolutionary ancestors) support the type of action-perception loops required to learn SMCs? To address this very general question, we begin with a concrete example.

Research on the sensorimotor systems that underpin vibrissal active touch in rodents has identified an underlying neural architecture of nested sensorimotor loops that extend from the hindbrain to the cortex (Kleinfeld et al. 1999). In this system, which to a large extent reflects the organization of other mammalian sensorimotor systems, it is not helpful to distinguish components as being specifically sensory or specifically motor, despite standard nomenclature (e.g., primary somatosensory cortex or primary motor cortex). Due to the existence of tight feedback loops that connect sensing (deflection of the vibrissae) to action (movement of the body and of the vibrissae), it is more beneficial to decompose the system in terms of anatomical levels (hindbrain, midbrain, forebrain) and their interactions in loops that are closed through the world (Kleinfeld et al. 2006), rather than in terms of a feedforward architecture from sensing to action. This approach has been usefully extended to the design of artificial vibrissal sensing systems for biomimetic robots (Prescott et al. 2009), suggesting that action-perception loops—of the kind necessary to learn SMCs—constitute a useful organizational principle of the brain.

Development of SMCs across Several Levels of the Neuraxis

Can action-perception brain loops support the gradual acquisition of simple-to-complex SMCs necessary for action control and, most importantly, for the development of cognitive abilities? It has often been argued that a primary requirement for a living organism is the ability to manage adaptively with situated choices, not complex cognitive operations, and that the brain circuits originally

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developed to address the former might have been successively reused and extended for the latter (Cisek and Kalaska 2010; Pezzulo and Castelfranchi 2009).

We propose that SMCs develop across several levels that eventually could encompass intelligent or abstract cognitive functions.[4] (For brevity we do not focus on prenatal development, but it is likely to be important in this process and should not be ignored in a holistic take on these issues.)

Spinal sensorimotor loops are the first SMCs to develop in the somatosensory system. The next step could be the emergence of transcortical loops (somatosensory feedback which reaches the neocortex and activates the corticospinal tract). This may help extract more complex patterns of physical interactions and enable the extraction of semantic meaning at the perceptual level (feature detection), first at primary sensory cortical neurons and thereafter through proper connections with primary output cortical areas. At this level, information processed in primary cortical neurons is, to a large extent, still constrained by physical rules of the external world because of their proximity to the sensory receptors and muscles at the level of the neural connectivity. This process could accompany bodily physical maturation to the adult level, to complete the acquisition of SMCs necessary for physical interactions, and also to complete perception-action loops between the cognitive agent and the environment.

At the next stage there would be the formation of corticocortical circuits with higher association areas. Here, the information processed becomes gradually detached from physical sensorimotor rules and can thus be regarded as abstracted. There would be a constraint, however, in that the areal patterns of corticocortical connections and intracortical information principles should be largely conserved across the cerebrum, including sensorimotor associations. This stage of development proceeds under the mismatch of bodily (bodily completion) and neural (late completion, especially higher association areas where development continues until the late twenties in humans) development, namely adolescence. Social complexity during puberty would largely contribute to acquisitions of mechanisms for information processing at this stage, most of which are not instrumentally measurable.

Whereas the acquisition of SMCs is largely a matter of finding correlations between motor acts and patterns of sensory feedback, a similar mechanism can, in principle, be extended to complex cognitive and social domains, based either on SMCs or on "second-order" contingencies. In the social context, an individual can probe the responses of other persons by acting in different ways, in analogy with the sensory feedback. Different social interactions will generate varying sets of responses, which might form the basis for learning a (predictive) model of the interaction between the self and other people. At a more

4 Illustrative videos can be found in the webpage of the Center on the Developing Child, Harvard University (http://developingchild.harvard.edu/resources/multimedia/videos/three_core_concepts/brain_architecture/), accessed on January 19, 2015.

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advanced stage, this mechanism could permit acquisition of societal (a set of persons) models and how we predict that their interrelations will change under different (probing) conditions. In social settings this mechanism is boosted by other, not strictly sensorimotor, ways of acquiring models, especially through verbal communication. Linguistically mediated acquisition plausibly capitalizes on existing models—sharing some commonalities with them—but also opens new horizons, ultimately leading to abstract concepts, in ways that are incompletely known. Emotional components to cognitive thinking could be acquired through similar associative learning (e.g., when a child gets emotionally rewarded when exploring mathematical problems). This could confer a degree of individualization if the pattern of social rewards differs from individual to individual.

Several indications suggest that not only environmental but also genetic factors influence brain development. For example, there is a robust cerebral asymmetry in the newborn (Glasel et al. 2011), and it is believed that the early maturation of the language areas in the left hemisphere of the brain provide the basis for a start-up kit for language learning (Leroy et al. 2011).[5]

Brain Mechanisms Supporting Low- to High-Cognitive Abilities: A Computational Perspective

The traditional distinction between the domains of low- and high-level cognition (König et al. 2013) might not necessarily correspond to separate cortical operations. Instead, it might support a unified description in terms of hierarchies of loops that progressively "abstract" from sensorimotor domains.

Although we lack a comprehensive computational and mechanistic framework to describe this "abstraction" process, recent advancements in computational and systems neuroscience might offer insight into how this might be possible. A series of experiments using the distributed adaptive control robot architecture illustrates how a robot can progressively acquire increasingly complex behaviors (e.g., spatial navigation abilities) by starting from a small repertoire of initial reflexes. These reflexes support the acquisition of object and affordance representations which, in turn, form the basis to acquire hierarchies of procedural plans that permit the robot to optimize behavior over longer timescales (Verschure et al. 2003, 2014). From a different but related perspective, namely *active inference*, the brain is viewed as a statistical inference machine that encodes SMCs and other regularities using hierarchical models. Importantly, the functioning of the models at different hierarchical layers is not fundamentally different; however, they operate at different timescales (faster for the lower models, slower for the higher models) and thus can drive perception

[5] It is commonly believed that there may also be innate reflexes, but one factor of uncertainty to be tested in future studies is to what extent the biomechanical and anatomical properties of our bodies participate in dictating the emergence of these reflexes.

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and action planning on different time horizons (e.g., proximal actions at the lower levels vs. distal plans at the higher levels) (Friston 2008, 2010).

Still another related approach asks whether the neuronal coding required for lower (e.g., sensory processing) and higher cognition might emerge by using (repeatedly) common optimization principles during learning or development. "Normative" approaches based on optimization principles have long been used to study sensory processing. For example, Olshausen and Field (1996) demonstrated that the optimization of sparse (and well-discriminable) representations over a universe of natural stimuli leads to response properties akin to simple cells in primary visual cortex. Furthermore, optimally stable/slow responses offer an explanation of complex cells in primary visual cortex (Berkes and Wiskott 2005; Körding et al. 2004). Subsequent studies extended this approach to higher levels in the visual hierarchy and other modalities (Berkes and Wiskott 2007; Dähne et al. 2014; Klein et al. 2003; Wyss et al. 2006).

In the original studies of Barlow (1961), the "sparsity" of representations derived from considerations of energy efficiency. More recent work, however, has shown that they can also be seen as approximations of *optimal predictability* in light of the subject's own action repertoire (König and Krüger 2006). This latter formulation links more directly to action-based theories, because an agent essentially builds a neural code that permits encoding and exploiting SMCs efficiently rather than just capturing the statistics of sensory events. This suggests that the same principles might be reused from sensory to more complex cognitive domains. Indeed, if the principle of *optimal predictability in light of one's own action repertoire* is replicated at higher hierarchical levels, sparse activation patterns are produced, corresponding to local and analogue activation patterns such as feature maps in low-level areas, up to binary, structured and disambiguated activation patterns (possibly implementing properties of symbols and syntax) at higher levels (König and Krüger 2006). At lower levels this mechanism produces sensory-related invariances (e.g., perceptual features), whereas at higher levels it produces action-mediated invariant representations of objects and affordances, in the sense that the properties defining an object (as an invariant) are not perceptual (like its color) but action-related, or the fact that a person can only execute certain actions on it (König et al. 2013). Accordingly, the activation of high-level neurons would not express passive object properties but "directives" (Engel et al. 2013) or inclinations of interactions with the objects, also possibly supporting so-called *predictive analogies* (Indurkhya 1992) with objects or events in another domain where it is still possible to apply the same set of actions.

To summarize, these arguments suggest that the repeated application of the *optimal predictability* principle would produce a natural transition from processing steps largely governed by external properties of external objects toward an active view of object interaction, thus possibly linking the acquisition of simple-to-complex cognitive abilities.

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Open Questions

These examples illustrate that an action-oriented view can tackle important problems in a novel way, by considering the neural requirements for connecting sensory and motor streams as well as the nature of the learning problems to be solved by the brain. Although the computationally motivated hypotheses reviewed here require further empirical support, they illustrate how homogeneous processes of sensorimotor learning, hierarchical modeling, and optimal predictability might—at least in principle—explain the development of higher cognition in continuity with lower-level sensorimotor operations. Some domains of higher cognition demonstrate the predictions of the mechanisms sketched here, or similar ones, and have been investigated empirically: language (Pulvermüller 2005) and tool use (Maravita and Iriki 2004). The limitations of the action-oriented framework and the best way to test these empirically remain to be explored through future research.

Learning from Experiments on the Development of New SMCs

From an action-oriented perspective, interaction is claimed to shape (or at least contributes to the shaping of) fundamental categories (e.g., space and time) as well as basic phenomenological experience. However, to what extent this is possible is currently unknown. Ongoing research is addressing this problem using "sensory substitution" systems, which allow "new" (for our species) SMCs to be experienced.

Is It Possible to Acquire New SMCs and What Does It Imply?

The SMC theory holds that the quality of perception is constituted by mastery of SMCs; that is, the statistical relation of sensory changes and one's own actions (O'Regan and Noë 2001). As a corollary, introducing a new lawful relation should result in a new type of perceptual quality. An empirical test of this prediction was performed by using a newly developed sensory augmentation device (Kaspar et al. 2014; Nagel et al. 2005): a belt which translates the reading of a magnetic compass to a vibratory signal at the waist, always pointing north. This established a new SMC and permitted the effects of learning to "master" it to be scrutinized. After extensive training, subjects reported profound changes in perception: an enlargement of peripersonal space, increased use of egocentric reference frame, and enhanced security in navigation. Thus, a basic assumption of the theory of SMCs passed this empirical test.

None of the subjects, however, reported the development of a perception of the magnetic field as such, which would count as a truly novel experience for our species. At first glance, this does not seem noteworthy, as the orientation of the local magnetic field is of no behavioral relevance, but the consequences

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for spatial navigation are noteworthy. However, a sense of space preexists in normal subjects (cf. blind subjects; Kärcher et al. 2012) and is supported by vision, audition, and touch. Thus, perceptual changes induced by the sensory augmentation device appear as strong modifications of a spatial sense, not as a genuinely new and unique modality. Kärcher et al. (2012) conjectured that incomplete learning of a new modality resulted because the experimental subjects were well beyond the age of twenty. Only at a young age is the full set of mechanisms of neuronal plasticity available to support learning of SMCs. This defines a specific modality in support of a *transparent* perceptual access (t-SMC). "Transparent" refers to the common feature of sense modalities that present objects to us (and not percepts), as opposed to opaque processes, such as imagination, in which not the object but a mental image is presented to us (Martin 2002). When an individual is older (i.e., after the critical period of development), not all mechanisms of neuronal plasticity are available (Hubel and Wiesel 1970). This means that learning new SMCs will happen on top of preexisting SMCs. Perception, then, is not fully transparent, but defined by the preexisting modalities with which perception is associated—hence the term *associative SMC* (a-SMC). Thus, as demonstrated by Kärcher et al. (2012), adult subjects would be incapable of learning a truly magnetic sense; they would learn only a modification (albeit profound) of an already existing space perception.

Other Possible Effects of Learning New SMCs

The insights gained using an action-oriented approach might allow us to explain aspects of other phenomena, such as synesthesia and phantom limbs. In the paradigmatic case of color-grapheme synesthesia, viewing graphemes induces the perception of colors. For example, the letter "a" printed in black and white is perceived as red. The processing of graphemes involves the visual word form area, located directly anterior of human visual areas involved in color perception. Given present knowledge, it is highly plausible that this area supported different functions (e.g., object and face processing) before reading was learned (Dehaene and Cohen 2011). Thus the process of learning to read and process graphemes involves large-scale plasticity and possibly a "recycling" of the cortical network. A reduced capacity of neuronal plasticity (a-SMC) would lead to processing of graphemes but give rise to perception building on top of the already established visual-color SMC, thus leading to the perception of synesthetic colors. Hence, the phenomenon of synesthesia can be understood as maladaptation in the process of learning caused by a reduced set of plasticity mechanisms (a-SMC). Similarly, the phenomenon of phantom limbs can be analyzed. When a limb is lost in an accident, the respective cortical region is devoid of its original input. Due to neuronal plasticity, this input is substituted by other signals originating (or targeting) neighboring cortical areas. At a very young age, this plasticity is complete and gives rise to

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"normal" perception (t-SMC). However, after the age of six years, the fraction of patients experiencing phantom limbs rises quickly. Touching proximal parts of the body gives rise to the perception of a phantom limb (a-SMC).

All three phenomena—perceptual changes in adult subjects trained in a sensory augmentation device, synesthesia, and phantom limbs—could be understood as consequences of a reduced capacity of neuronal plasticity not giving rise to a fully transparent SMC as in early age, but to adapted processing still associated with the quality of perception of previously established SMCs. This suggests that there might be at least two phases in the development of action-derived cognition. In the first, a foundation is established; this might include the pre-wiring of subcortical systems and the acquisition of basic action-effect associations that can be used to drive basic actions in intentional ways, as well as a critical period for acquiring t-SMCs. During the second phase, brain plasticity still allows SMC-based learning but in ways that are constrained by the existing machinery; this would lead to developing a-SMCs and not t-SMCs. Despite these initial findings, several aspects of the acquisition of novel SMCs remain to be investigated (for a controversial discussion on early experiments aimed at manipulating perception by providing an "upright vision," see Kohler 1951).

Do We Need a New and More Interactive Method to Study Cognitive Development?

It is intrinsically difficult to study experimentally a multifaceted phenomenon that involves the brain, body, and environment over extended periods of time. An action-based view of cognitive development poses additional hurdles. Focusing on "active" agents—where "active" includes also "free" spontaneous (intrinsically motivated) exploration—is problematic for classical experimental paradigms, as these measure responses to controlled stimuli and are thus too restrictive from an action-based perspective.

Novel empirical methods are needed to address action and interaction. Many classical paradigms in cognitive psychology and neuroscience attribute a passive role to participants: predetermined stimuli are given and participants respond by choosing between predefined alternatives. Currently, several groups are working on methods to study cognition and cognitive development that will be more compatible with an action-oriented perspective (for a review, see Byrge et al. 2014). Below we review two important methodological aspects that need to be taken into account.

Decomposing the Development of Action Cognition

The classical "cognitive" approach and various versions of *enactivism* that are part of the action-based framework (for terminological clarifications, see Dominey et al., this volume) imply different ways of "decomposing" the issue

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of how action cognition develops. This, in turn, affects the methods used to study the development of action cognition. These two approaches differ with respect to who they regard as having the authority to define units of analysis. The classical approach assumes that scientists are entitled to do this, and that the priority is to find components which allow good prediction and control. Often, the variables of interest are the behavior of an individual or its brain state. Some types of enactivism, informed by phenomenology, assume instead that the units of analysis must honor the experience of the subject or agent (Gallagher 2005; Maturana and Varela 1980). For example, in a tool-use study, a subject feels that the tool is part of its own body. In this case, the unit of analysis could be "the subject plus the tool" rather than just "the subject," because from an enactivist perspective the subject and the tool form a system that should not be disentangled.

Moreover, the enactivist approach might consider contextual task elements in a different way than they are treated in traditional cognitive approaches. For example, in a categorization study, a cognitive psychologist usually groups various stimuli into different (fixed) categories for the purpose of statistical analysis. The enactivist might claim that the only, or most important, way to understand and categorize stimuli effectively is with respect to the ways in which subjects interact with objects (construed broadly). Stimuli might be grouped together according to kinds of subject-environment interaction. Stimuli that might have been treated, in the past, as the same (different) should be treated as different (same) depending on what is found in pre-experimental trials that measure ways in which subjects interact physically with potential stimuli. This would also mean that at each specific session or depending on a specific context, action cognition and its development can be decomposed differently.[6]

One important issue for future research is to assess the relative contribution of these two approaches to the study of cognitive development and to search for possible ways to integrate them. Some clues to unify the two contrasting views could come from the use of common computational approaches and "languages," including for example dynamical systems, complex systems, and hierarchical probabilistic methods, which are being successfully used in the study of cognitive development (Byrge et al. 2014; Pezzulo et al. 2011; Tenenbaum et al. 2011; Thelen et al. 2001) but require further elaborations through future studies. For example, some of the methodologies developed

[6] Consider an analogy with so-called Western and Eastern ways of thinking. Enactivists often refer to Buddhism and Mindfulness through meditation and holistic ways of thinking. As a simplified illustration of this contrast, the West is interested in objects (what) as units and in trying to formulate principles to relate and structure those units, whereas the East is interested in forms of relations (how) as units and trying to formulate structures of nodes to establish procedures to unify those units. "What"-oriented ways of understandings tend to appear static and reductionistic, whereas "how"-oriented understandings appear dynamic and holistic. This simplified illustration is offered just to exemplify the fact that both stances try to understand the same subject, albeit from different perspectives.

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within the dynamical systems tradition can be used to define the most valid units of analysis inductively, in a way that might align well with enactivism. In this perspective, the most useful units of analysis to describe a given phenomenon (e.g., how parent-children dyads coordinate their actions) would result from an analysis of which "order parameters" regulate the dynamical interaction of the dyad. This is analogous to the way interpersonal distance and relative velocity have been used as "order parameters" to study the dynamical interactions of dyads (e.g., attacker-defender dyads) in sports (Araújo et al. 2006; Kelso 1995).

The Role of Robotics in the Study of Cognitive Development

Developmental processes span extended periods of time and many levels of complexity in behavior. To study this, it may be beneficial to complement traditional experimental methodologies, which are usually directed at isolated levels of behavior, with robotic approaches, which are naturally interactive and have the potential to consider several important determinants of cognitive development simultaneously (e.g., bodily actions and the situated and social aspects of a given cognitive task to be developed). The synthetic approach of robotics should be (and in some cases already is) synergistically fused with the experimental approach.

Developmental robotics seems to be particularly suited for this purpose. It is a small field that is organized primarily along two strands: (a) taking inspiration from human and animal development, it aims to build machines capable of *open-ended development* in the real world (an engineering goal); (b) it uses robots as tools to expand understanding of human development. Robotic models can be used in several ways to help us understand human cognition and its development (for an analysis of these various ways and concrete examples, see Oudeyer 2010). For example, specific data can be modeled from developmental sciences, often through collaboration between roboticist and developmental psychologists, neuroscientists, or linguists (for speech and language development mechanisms, see Broz et al. 2014; Moulin-Frier et al. 2014; Yurovsky et al. 2013; for language formation, see Steels and Belpaeme 2005). In addition, novel hypothesis can be concretely formulated, leading to novel experiments with humans (e.g., regarding the brain and behavioral mechanisms of intrinsically motivated exploration, see Baranes et al. 2014; Mirolli and Baldassarre 2013).

Despite these initial, promising results, a gap exists between the potential of robotic modeling of development as a tool to study cognitive development and its impact on the field. Progress in the field could benefit from more systematic exchanges between the "synthetic" method of robotics and the experimental paradigm (Pezzulo et al. 2011).

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Conclusions and Open Challenges

An action-oriented approach has the potential to offer a much-needed unifying framework for the study of cognitive development, as it integrates multiple factors (e.g., sensorimotor learning, sociality, genes) and re-describes them from an action-based perspective (e.g., by asking which genetic biases can be considered to be action-based or useful to acquire SMCs). A research agenda for action-based cognitive development should consider how all these factors (and possibly others) are integrated, how they interact over time (for an initial proposal, see Figure 4.1), and what action-oriented aspects of development explain higher cognitive abilities.

One source of difficulty in research is that the most widely used empirical approaches to the study of cognitive function have intrinsic limitations in the study of action-based cognitive development. Subjects do not simply respond to stimuli predefined by the experimenter but are intrinsically "active" and "exploratory." Moreover, long timescales are involved in cognitive development, as are various interacting factors.

Consider, for example, the learning of a musical instrument. At a certain age, children are able to begin the process of acquiring the skills necessary to play an instrument (e.g., piano or clarinet). Skill learning results from a combination of at least two interacting processes: one domain general, the other context specific (e.g., linked to a specific musical instrument). A domain-general ability for sequence learning permits finger movements to be executed. It is not, however, tied to the mastery of a musical instrument but rather provides the prerequisite "substratum" or "scaffolding" to acquire musical proficiency. Whether a child learns finger movements needed to play the piano or clarinet is determined by the context, as sequence learning is specific to that particular instrument. The study of how a specific ability develops needs to distinguish whether the impact of sensorimotor learning on cognitive development depends on the "scaffold" or on the specific "contents" of the behavioral repertoire that a child learns.

To overcome such difficulties, we need to consider integrating different research traditions and incorporating ideas from dynamical systems and robotic approaches. Care must, of course, be taken to avoid simplifying the phenomenon of interest too much (e.g., taking a too reductionist or behaviorist perspective on what cognitive skills or concepts are and how they are acquired).

Ongoing research is currently investigating the key claims of action-oriented cognition and related embodied and enactivist approaches (Barsalou 2008; Byrge et al. 2014; Engel et al. 2013; Glenberg and Kaschak 2002; O'Regan and Noë 2001). Not all of these studies have investigated the *development* of action-based cognition, and additional research is needed to fill this gap. To begin, several ways that important hypotheses might be tested include the following:

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- A fundamental challenge will be to assess the causal relation between action-based processes and development. Action-oriented theories suggest that cognitive abilities and the behavioral repertoire develop in parallel, but these two aspects diverge repeatedly during human development. Initially, infants have little control over their limbs, yet they readily engage in social interactions with other humans. Cognitive abilities seem to be more advanced than sensorimotor skills. There are, however, cases where an expansion of the behavioral repertoire does not readily correspond to an increase of cognitive abilities, such as when children who are supposedly able to *predict* the (sensory) consequences of their actions fail to *understand the implications* of executing an action (e.g., whether the action can cause harm). Do such mismatches in either direction suggest that cognitive development and the expansion of behavioral repertoire occur independently? For example, the ability to judge intentions in young children, contrasts with their use of this ability in laboratory experiments. More empirical research is needed to answer this question.
- After children master abstract concepts, it would be interesting to test whether the sensorimotor conditions under which an abstract concept was acquired continue to drive a child's application of that concept or reasoning with it. Such tests might involve exposure to potentially interfering sensorimotor stimuli (of the sort that facilitated acquisition) to see whether such stimuli continue to affect processing in abstract reasoning tasks and, if they do, to determine the precise nature and extent of their effect. In this way, we might test the extent to which concepts are, even after mastery, partly sensorimotor. This could constitute part of a larger program to test the "detachment" of abstract concepts from all sensorimotor conditions during cognitive development (Pezzulo and Castelfranchi 2007).
- To investigate whether sensorimotor learning merely scaffolds the development of concepts, or scaffolds development and remains an important part of their representation/instantiation, participants (e.g., children) could be given a novel sensorimotor experience after concept acquisition and then tested to determine whether this changes their application of concepts. Another possibility is to study the effects of early appearing motor deficits (e.g., due to prematurity or other pre- and perinatal hazards). Is cognitive development slowed globally by a preexisting motor deficit, or are there specific effects on some but not all aspects of cognitive development? The ability to control vocalizations, hand movements, or facial muscles (disturbed in the case of Moebius Syndrome) are all known to occur as specific motor impairments from birth and thus might provide useful models for the study of fine-grained development of action-based cognition.

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- To test the extent that concepts become "detached" from sensorimotor function, one could look at bimanual amputees, in which a lot of what comprises the sensorimotor contingencies represented at the neocortex is lost. Current evidence suggests that these patients do not have a radically different conceptual world or model of the world (Aziz-Zadeh et al. 2012). To elucidate developmental effects, it would be necessary to observe children born with severe motor limitations, either due to brain abnormality or bodily malformations, such as absence of limbs. If the view of "second-order contingencies" holds, the neural processing of abstract concepts might require the extrapolation and differential activation of nonsensorimotor aspects of experience.

Developmental robotics may offer novel insights into the mechanisms of action-based cognitive development (Cangelosi and Schlesinger 2014). Current studies are providing concrete mechanisms of proximal drivers for exploration, like *intrinsic motivation* or *curiosity*, and showing that they can automatically structure developmental stages in the long term—from the development of sensorimotor affordances to the onset of speech communication (Oudeyer and Smith 2016). Models of intrinsically motivated exploration, which drive the organism to explore through maximizing the reduction of prediction errors, combined with social guidance and motor synergies have demonstrated how such interacting mechanisms can self-organize a "learning curriculum," shaping the steps that progressively lead an organism to learn increasingly more complex contingencies (e.g., in the domain of early vocal development in infants; Moulin-Frier et al. 2014). These models provide precise predictions regarding the nature of these intrinsic rewards, as well as on behavioral consequences of such a self-generated curriculum (Gottlieb et al. 2013). An intriguing aspect of this research is that it might allow us to understand how developmental trajectories are constructed by a cognitive agent over time as a result of autonomous exploration rather than depending on fixed predefined stages. This speaks directly to a view of development as an *active* process.

The pursuit of these and other research directions holds promise to improve our scientific understanding of cognitive development by contributing to a much-needed theoretical synthesis of an action-based approach—one that will impact future education and technology.

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