Cognition from the bottom up: on biological inspiration, body morphology, and soft materials

Rolf Pfeifer¹, Fumiya Iida², and Max Lungarella³

¹Artificial Intelligence Laboratory, Department of Informatics, University of Zürich, Andreasstrasse 15, CH-8050 Zürich, Switzerland
²Bio-Inspired Robotics Laboratory, Institute of Robotics and Intelligent Systems, ETH Zürich, Leonhardstrasse 27, CH-8092 Zürich, Switzerland
³Dynamic Devices AG, Technoparkstrasse 1, CH-8005 Zürich, Switzerland

Traditionally, in cognitive science the emphasis is on studying cognition from a computational point of view. Studies in biologically inspired robotics and embodied intelligence, however, provide strong evidence that cognition cannot be analyzed and understood by looking at computational processes alone, but that physical system–environment interaction needs to be taken into account. In this opinion article, we review recent progress in cognitive developmental science and robotics, and expand the notion of embodiment to include soft materials and body morphology in the big picture. We argue that we need to build our understanding of cognition from the bottom up; that is, all the way from how our body is physically constructed.

Introduction

The classical approach to the study of cognition advocates a deliberate abstraction from the physical realization of a cognitive system to the level of computation or information processing¹ [1–7]. In a recent paper this abstraction was characterized as follows: ‘Cognitive science has been dominated by a view of cognition as computation over mental representations’ [8], see p. 202. This view has been very productive, at least in the initial stages of cognitive science. However, over the past two decades many criticisms have been voiced and alternatives have been proposed integrating concepts such as self-organization and embodiment; that is, the reciprocal and dynamical coupling among brain, body, and environment [8–18]. If we take, for example, the characterization of cognition found in [8] as the ‘exercise of skillful know-how in situated and embodied action’ (see p. 202), it is clear that this has little to do with information processing in the classical sense—a conceptual turn (or rather, a paradigm shift) whose import can hardly be overestimated.

Although there seems to be increasing agreement that the body plays an essential role in cognition (see, for instance, any of the references listed above), there has been relatively little work on detailing what the connection between brain and body looks like, how it shapes and drives our actions, and how it manifests itself in brain processing and behavior. In this opinion article, we attempt partially to fill this gap by discussing some essential prerequisites for higher-level cognition and intelligent behavior to emerge. We do so by giving illustrations and case studies from artificial intelligence, robotics, and human behavior. It turns out that robots can serve as highly productive tools to investigate fundamental issues in cognitive science. Moreover, following a recent trend in biologically inspired robotics, we expand the notion of embodiment to include soft materials and body morphology in the big picture. The main challenge is to connect two seemingly disparate areas: morphology and materials on the one hand and intelligence and cognition on the other.

Not only brains, but entire organisms

Traditionally, biological inspiration in the cognitive sciences has centered mostly on the modeling of brain areas and psychological phenomena such as memory, perception, language, categorization, and learning using methods from neuronal information processing (e.g., [20–24]). Biological inspiration in robotics, however, has not only focused on computational processes occurring in the brain but has incorporated the behavior of the entire (artificial) organism. By building physical models of animals, biologically inspired robotics (or biorobotics for short) has been advancing our understanding of locomotion, orientation and navigation, manipulation, perception, and actuation—areas where biological beings often outperform robots, which is why many engineers feel that if they understand biological principles and apply them to robots, they will be able to build more adaptive machines (e.g., [25–27]).

Exploiting materials: ‘soft robotics’ and morphological computation

An important characteristic of biological as well as robotic systems is their existence as physical (embodied) entities...
in the real world. Such systems have a particular shape or body morphology, are built (by evolution or through an engineered construction process) from certain materials, are endowed with sensory and motor systems, and are embedded within their respective ecological niches. However, biological systems, in contrast to artificial ones, especially robots, are made for the better part of soft materials (even in humans, the rigid skeleton comprises less than 15% of overall body weight; [28]). It stands to reason that soft materials (apart from the enormous plasticity of the brain) are largely responsible for the adaptivity, robustness, and resilience found in nature. It turns out, for example, that functionalities such as stabilizing the body, coping with impact in walking, or adapting to the shape of an object while grasping can often be partly taken over by morphological and material characteristics; for example, the damped elasticity of the muscle–tendon system or the deformable tissue in the hand and on the fingertips. It is as if the brain were outsourcing some of the control – or computation – to morphology and materials, which is why this phenomenon is called morphological computation (Box 1). In this way, processes such as coping with small mechanical perturbations caused by unevenness in the ground, which require extremely rapid responses, can easily be taken care of by the body. Drawing from these observations and enabled by a combination of new materials and fabrication technologies, an emerging interdisciplinary subfield of biorobotics – soft robotics (Box 2) – has been exponentially gaining momentum over the past few years, as demonstrated by the many novel results, insights, and fascinating robots that have been produced (Figure 1). However, what has been missing so far is an understanding of the relation of soft robotics to cognition and intelligence.

Connecting cognition, morphology, and materials
Cognition can be studied, in essence, at three different timescales: (i) the ‘here and now’, which investigates the mechanisms of how, for example, grasping is achieved; (ii) the developmental timescale, which studies how these abilities come about through learning and maturation of the organism; and (iii) the phylogenetic timescale, which looks at the evolution of organisms over many generations (Figure 2) (see [14], derived from [29]). As we argue here, a developmental/learning point of view provides exactly the necessary concepts to bridge the gap between cognition, morphology, and materials. Starting with the evolutionary perspective, we introduce the different timescales and discuss how they interact.

What we now call cognition or intelligence (and the brain, its physical ‘substrate’) has always evolved as part of a complete organism that had to survive and reproduce in the real world. Because the body is the only way in which organisms can communicate with the environment, we have to investigate how brain, body, and environment interact to understand brain–body coevolution. Embedded into the evolutionary cycle there is a process of ontogenetic development that gets its initial conditions from evolution but is continuously shaped by physical (and social) interaction with the current environment (e.g., [30,31]).

Simulating mind–body coevolution
The plethora of compelling designs brought forth by biological evolution has always been a source of inspiration for researchers and engineers and led to the inception of the field of artificial evolution. In the 1960s, 1970s, and 1980s this was mostly about using computer programs for
Box 2. Soft robotics

In recent years, a new field in engineering has been emerging and growing rapidly – ‘soft robotics’. Soft and deformable structures are crucial when dealing with uncertain and rapidly changing task environments. Unsurprisingly, biological systems largely comprise soft, deformable materials [26,67-69]. Softness can dramatically simplify interactions with the environment; for example, grasping and manipulation of objects of unknown shape, locomotion in rough terrains, and physical contacts with living cells and human bodies.

Soft robots typically have unique characteristics compared with conventional rigid robotic systems: they have elastic and deformable bodies that entail a large (often infinite) number of DOFs; and they have continuum bodies with no clear separation between components such as sensors, actuators, and supporting structures (e.g., skeletons). They often comprise unconventional smart materials such as hydrogels, conductive polymers, or temperature-sensitive alloys that can potentially endow passive structures with sensory–motor capabilities. Robotics researchers are investigating these physical properties because conventional rigid-design strategies are known to considerably limit robots’ capabilities, especially in uncertain, unstructured, and dynamic task environments.

Owing to the rapid development of novel fabrication techniques and the availability of smart materials, there have been many achievements in soft robotics that are also highly relevant to cognitive science. For example, a novel design method for soft electronics was applied to construct bendable photoreceptor arrays [71]. Flexible reconfiguration of photoreceptor geometry allows us to investigate the influence of visual sensor morphology, which has been shown to perform a kind of preprocessing for the brain [i.e., a morphological computation (Box 1)].

On the motor side, pneumatically driven actuators are often used in soft robotics applications because they are not only small, powerful, and simple to fabricate, but are also easy to control for a large variety of tasks; for example, in snake-line robots for locomotion in complex environments, as soft exoskeletons [72], and in robotic hands for grasping unknown objects [73]. Soft robotics research is also necessary for 3D printing because constituent materials have to be liquefied and properly deformed into target shapes. This technology can be used to change dynamically the mechanical properties of tactile sensors to adjust sensitivity and sensing range in situ [74]. All of these case studies imply that sensory–motor skills and the cognitive abilities such as categorization and body schema that are built on them are considerably influenced by the specifics of morphology and materials: they are distributed throughout the system, not centralized in a cognitive architecture.

Automated problem solving1, but later these methods started to be used in robotics as well [32–36]. The standard approach has been to take a particular robot and to evolve its controller, typically a neural network. Interesting results have been achieved, but there was the serious constraint that the body could not evolve (thereby giving up a huge adaptive potential), which was obviously not the case during biological evolution. Investigators pioneered by Karl Sims [37] started to develop systems for mind–body coevolution that often came up with unexpected morphologies and displayed fascinating behaviors (e.g., [38,39]). Today, these systems can, for example, perform navigation, locomotion, foraging, and categorization tasks and are able to compete for ‘food’, which is why some researchers call these systems ‘minimally cognitive’ [10]. However, the gap between robotics and cognitive science remains.

As mentioned above, biology teaches that the mind has not evolved in isolation, in a kind of ‘algorithmic ether’, but as part of a complete organism. However, it tells us little about the details of the interaction between mind and body. To start elucidating this aspect, let us look at some recent developments.

Perception through action: sensory–motor contingencies (SMCs)

In their seminal paper, O’Regan and Noé [40] discuss the crucial role of action for perception and in the development of higher-level cognitive capabilities. They introduce the concept of SMCs, which are essentially characterized as the structure of the rules underlying the systematic change of sensory stimulation produced by motor action. This idea can be traced back to John Dewey who in his influential essay entitled ‘The reflex arc concept in psychology’ argued that ‘we begin not with a sensory stimulus, but with a sensori-motor coordination, the movement of body, head and eye muscles determining the quality of what is experienced’ [41]. Dewey, in essence, proposed one of the most fundamental principles of intelligent behavior; namely, that every action has as a consequence patterns of sensory stimulation [14,42].

To understand how these patterns are induced, we need to look more closely at SMCs. The patterns of sensory stimulation generated depend on several factors: (i) the task environment (e.g., the object we are grasping); (ii) the physical nature of the sensors (e.g., visual through the eyes, haptic in the skin in the hand and on the fingertips); (iii) the placement and distribution of the sensors on the organism (eyes in the head facing forward, high density of tactile receptors in the face, on the lips, and in the hand and fingertips); and (iv) the particular action (holding a cup in the hand leads to very different sensory stimulation than does moving the hand over the edge of the cup).

Putting it all together: development

Let us now see how it all fits together. The Russian neurophysiologist Nikolai Bernstein, while pioneering the field of motor learning, asked the question of how the central nervous system of humans or animals learns to master a complex and varying musculoskeletal system with many redundant degrees of freedom (DOFs) to perform skillful movements [43]. Due to the large number of variables involved (at the anatomical, kinematic, and neurophysiological levels), trying to learn the control of all DOFs simultaneously turns out to be virtually impossible – a well-known issue that arises when dealing with huge high-dimensional search spaces dubbed the ‘curse of dimensionality’ [44]. Bernstein hypothesized that, in the developing or learning organism, many DOFs are initially ‘frozen’ or rigidly coupled together; for a reaching movement, for instance, we do not need to control all of the joints in the hand immediately – we need only a few in the shoulder and the arm (this reduction in DOFs is often visible as a stiffening of posture). Once reaching is in place, additional DOFs can be ‘freed up’ (for example, opening the hand while performing the reaching movement), thereby adding flexibility to the performance. In a sense, the learning process is historical;

---

1Frequently referred to as evolutionary or genetic algorithms.
that is, it builds on what has already been learned. A similar strategy seems to be used by babies and toddlers: they continuously adjust their body morphology by reorganizing their biomechanical DOFs, which in turn simplifies the control problem and accelerates motor learning. Also in this case, constraints on the search space are provided by the musculoskeletal structure of the body, biomechanical constraints, or, more generally speaking, the particular morphology.

The power of morphology and materials: illustrations
Although this ‘freezing–freeing strategy’ is a good conceptual model for illustrating the role of morphology in motor learning, the implications of the influence of morphology and material properties on the development of human cognition are far more reaching. A somewhat intuitive example is to think about the natural dynamics of our physical body. Assume that while standing, I let my arm swing loosely around my hip. Because of biomechanical constraints from the anatomy and the tissue (ligaments, muscles, and tendons) this movement requires little energy and little control because the control is – at least partially – incorporated into the shoulder–arm–hand system. The resulting trajectory of the hand in 3D space is highly complex, but there is virtually no explicit control about it. Despite the seemingly passive nature of the movement, due to the biomechanical bias, movement-related streams of correlated sensory stimulation are induced that, in turn, can drive motor learning (as illustrated by the ‘fetus simulations’ of Mori and Kuniyoshi [45] below).

The role of morphology and materials can also be explained in a slightly more complex motion-control task: grasping a glass. First, you look at the glass, then you reach for it; while approaching the glass you open the hand (pre-shaping) and finally you wrap your fingers around it by applying a certain force to the fingers. Note that by applying force, the fingers will automatically adapt to the shape of the object – you do not need to know its exact shape [46].

Figure 1. Trading control and materials: morphological computation. (A) An industrial manipulator, the KUKA lightweight robot, comprising rigid limbs and actuated joints to suppress mechanical dynamics for precise-positioning tasks. (B) The Lokomat™ robotic gait-training orthosis is an impedance-controlled exoskeleton with actuated hip and knee joints used for robot-assisted walking therapy (see also Box 3). (C) Passivity-based bipedal robot capable of energy-efficient walking (for more details, see Box 1). (D) Soft, wearable glove for grasp-assistive device. The actuators (red components around the fingers) are made of soft silicon that can be pressurized or depressurized to assist human grasping motions [75]. (E) Roboy, a humanoid robot comprising biologically inspired musculoskeletal structures. The robot uses tendon-driven actuation that enables soft and flexible motions of the skeletal structure. (F) Octopus-arm robot made of soft silicon and featuring tendon-driven actuation. The morphology and material of this arm provide high conformability of the structure to objects in contact [76]. (G) Soft gripper based on particle jamming. The gripper (blue component in the photograph) comprises a balloon filled with particles that generate grasping forces when the balloon is evacuated. The softness of the balloon allows the gripper to adapt to almost any shape of grasped object [77]. All of the robots (A–F) are capable of exhibiting adaptive behaviors, although the examples on the right exploit more morphological and material properties in their behaviors than those on the left.
Moreover, because the tissue in the hand and on the fingertips is soft, it will also adapt to the shape of the object passively, not centrally controlled – it is only the softness of the material that accounts for this. Lastly, because the skin is always a little humid, it has the right frictional properties. Imagine having to grasp the glass with metal thimbles on all of your fingers; it would be next to impossible – a nice illustration of what materials do for us.

Let us consider further what happens in the processing of sensory signals while grasping, for example, a cup in the hand. There is an evolutionary predisposition for the palm of the right hand to face left, which makes it easy to grasp the object. Grasping has several effects. First, I am (obviously) holding the cup in the hand. Second, because of the particular biomechanical constraints, the most natural and energy-efficient behavior is to move the hand toward the center in front of the body, which brings it into the middle of the visual field. In this way, task-relevant visual stimulation is induced (this would obviously not be the case if the eyes were physically located at the heels). Third, because of the grasp and thanks to the high density of tactile receptors in the hand and fingertips, rich patterns of tactile sensory stimulation are generated. Fourth, as a result of the proprioceptive sensory stimulation, I can feel roughly how big and heavy the cup is. Last but not least, visual and tactile information are integrated cross-modally; that is, the visual size and the felt size of the cup are combined into a single percept. This thought experiment illustrates the fact that the statistical regularities induced in the sensory channels depend on the morphology because the morphology constrains the actions, which in turn entails other patterns of sensory simulation, and therefore what is learned will be different for different morphologies.

**Correlations through sensory–motor coordination**

Through experiments with real and simulated robots, it has been shown that the sensory stimulation induced by a sensory–motor coordinated action (such as grasping or following a person with the eyes) incorporates statistical regularities and information structure [47–49]. Moreover, the sensory signals present in different channels are correlated across each other and this correlation is achieved through the physical interaction with the environment, not through processing in the brain. These patterns of correlated sensory stimulation constitute, so to speak, the ‘raw input’ that the brain processes to learn something about the world and to create coherent cognitive states. They are a prerequisite not only for any form of attention to filter out irrelevant signals from a massive sensory data flow, but also to form cross-modal associations that in themselves are necessary for concept formation (e.g., [17,31,49]). This implies that we can learn to predict the stimulation in one sensory channel (e.g., the haptic) from that in the other channel (e.g., the visual); by just looking at the glass, I already have an expectation of what it will feel like when I grasp it.

**A cure for the curse of dimensionality?**

Now we understand a little more about the influence of morphology, materials, and behavior on sensory stimulation and motor control, but how can we put these ideas together to understand human cognitive development or, more provocatively, to solve the problem of dimensionality?

A possible approach to address this challenge can be discussed in the context of the reafference principle. This principle, which can be applied to the control of movements, states that a copy of a motor command is stored together with the expected pattern of sensory stimulation and is compared with the actual feedback provided by the sensors (the reafferences). Based on the result of this comparison, the signal is then modified so that, over time, the real feedback matches the efference copy [50–52]. By applying the reafference principle, we can explore our own body dynamics; that is, we can establish the relation between the motor signals and the multimodal patterns of sensory stimulation induced by the movement. In other words, based on motor signals, we can build expectations that predict the consequence of particular actions before sensory feedback is available (see also Figure 2). Ultimately, this leads to the formation of a body schema [53] that can predict the consequences of motor actions and be used for achieving goal-oriented behaviors. Although many issues remain, this theoretical framework may support a systematic exploration of cognitive development in a bottom-up manner.

**Changing morphology: the synthetic approach**

There is a growing discipline – cognitive developmental robotics – that embeds models of biological, neural, and physical development in robots with the goals of

---

1Note the interaction of the phylogenetic and here-and-now timescales (Figure 2).
understanding human cognition and designing artificial cognitive systems [54–56]. The theoretical underpinning of this research endeavor is that, because phenomena occurring at developmental timescales are hard to study experimentally, it is necessary to adopt an unconventional strategy, also called the synthetic approach, that relies on building virtual agents (e.g., simulated animals, bio-inspired robots) and analyzing their behaviors [14].

An illustrative recent case study is the simulation of a ‘fetus’ that was used to investigate the influence of sensor morphology on motor development. Because we are so accustomed to our own body morphology, to the physical nature of our senses (vision, audition, haptics, and proprioception), and to the distribution of the sensory receptors on the body (eyes in the head facing forward, high density of touch sensors in the hand, on the fingertips, and in the face), it is hard for us to imagine how it could be different. But let us, for the sake of the argument, assume that their distribution could be modified. How would this affect the developmental process? Mori and Kuniyoshi [45], in groundbreaking work, simulated the neuromotor development of a fetus in the uterus with different distributions of haptic sensors. With a natural (nonhomogeneous) distribution, the fetus developed ‘normal’ kicking and jerking movements (i.e., similar to those observed in a human fetus), whereas with a homogeneous allocation it did not develop any of these behaviors (Figure 3). This is a dramatic illustration that the morphology – of which the physical nature and placement of the sensors on the organism is an essential part – can crucially affect motor development because the patterns of sensory stimulation resulting from initially random movements will be very different for different distributions, which in turn influences neural development [57]. It also shows the power of development (natural and artificial) and of how sophisticated, seemingly goal-directed behaviors can emerge from random ones. These processes are enabled through the morphological constraints of an embodied system.

**Reflexes from self-organization**

Although it is already intriguing to study the influence of sensor morphology on the development of cognition, other developmental phenomena can also be explored. For instance, simply lifting a leg from the ground requires the concerted activation of many muscles and muscle groups responsible for the movement of the knee and hip joints. Moreover, as the motion starts, sensory–motor coordination, mostly at the level of spinal reflexes, kicks in: every muscle–tendon complex is equipped with numerous sensory receptors such as muscle spindles and Golgi tendon organs (which signal changes in muscle length and muscle tension) that form synapses directly with motor neurons in...
the spinal cord that, in turn, regulate the contraction of the muscles involved in the movement. The spinal reflexes also ensure that the muscles do not act against each other or that muscle tension does not exceed the limit beyond which damage to muscle fibers or joints may occur. These basic sensory–motor coordination circuits are the foundation of all motor behaviors in humans, but it remains largely unknown how they develop.

To get a better grip on the mechanisms underlying the development of such reflexes, Marques and his colleagues [58,59] used a neuromusculoskeletal model of a leg embedded in a simulated environment (Figure 4A). With this setup they conducted a series of computational experiments to study under what conditions basic reflexes can self-organize. They found that, under particular conditions, spontaneous motor activity in each muscle of the musculoskeletal model could lead to correlations in the sensor and motor signals (Figure 4B,C). These regularities were picked up by an unsupervised learning scheme, which resulted in the emergence of reflex circuits similar to those found in human fetuses. As one might expect, different morphological configurations of the musculoskeletal system led to the emergence of different types of reflex circuit (Figure 4D,E,F). An important discovery was that self-organization could occur only when the so-called Hill-type muscle model was used (i.e., one of the most widely used biologically plausible muscle models in biomechanics); self-organization was not observed when a series elastic actuator model was used (i.e., one of the most popular models in robotics research). The latter point will require additional investigation in future research.

This computational experiment shows that morphology influences cognitive processes not only through physical attributes or constraints such as where sensory receptors or muscles are located on the body, but also through how body parts such as muscles and tendons react dynamically to given stimuli through bodily material properties. In other words, without a better understanding of such
material aspects of embodied systems, we will not be able to fully understand how the body shapes the development of the central nervous system.

Open questions
We believe that we have convincingly argued that the morphology and the material properties of the body and neuronal information processing (or better, brain dynamics) are tightly interconnected because the raw inputs (i.e., the patterns of sensory stimulation) are generated through the physical interaction of the body with the environment. However, many tough questions remain.

First, will we ever be able, using this bottom-up approach, to engineer systems that are capable of mastering complex cognitive skills, such as language or mathematics, and that can handle or ‘understand’ other abstract concepts like responsibility and democracy? For example, in a highly provocative and inspiring essay George Lakoff and Rafael Nunez [60] (see also [61]) suggest that, by building on the notion of conceptual metaphors, this will indeed be the case. By conceptual metaphor, they refer to the understanding of an abstract idea in terms of a physical one; for example, framing the abstract idea of ‘importance’ in terms of ‘size’ or the mathematical concept of a ‘set’ in terms of a ‘container’. Much of the work presented by Lakoff and Nunez is grounded in empirical research (e.g., studying mathematicians’ gestures while explaining an abstract concept like a limit or infinity) but additional evidence will most certainly be required. We are convinced that robots and embodied-agent simulations can provide a highly productive test bed to deepen these ideas, because in robots and simulations, in contrast to humans, all motor commands and sensory stimulation can be recorded and analyzed in detail.

Second, what is the role of human interaction in the developmental process and how does it influence sensory–motor learning and skill acquisition? There is much evidence that sensory–motor tasks are learned more quickly through instruction, observation, and imitation, as examples of interactions between humans [42]. However, how should we construct smart machines or human–robot interfaces to enhance regularities in sensory inputs and elicit neural responses that promote motor learning and faster recovery after debilitating illnesses (see also Box 3 and Figure 5)?

Third, we have talked about concept formation by building cross-modal associations. What about the function of language in this process? There are fascinating experiments on language acquisition investigating this process, although the results remain preliminary. For example, Steels and colleagues, using partially embodied agents (physically movable cameras) demonstrated that, in a naming game played over the Internet, after a number of interactions a common vocabulary emerged in a population of agents [62,63].

Fourth, do organisms with different morphologies develop different kinds of cognition? For example, do congenitally blind children, because of their different ‘morphology’ (sensors) acquire other concepts and think differently compared with children with normal vision? According to the ideas presented in this opinion article, we can, without attributing value, expect rather fundamental differences (see also Mori and Kuniyoshi’s simulation experiments [45]). A similar question can be asked about children with movement disabilities. Again, because the patterns of sensory stimulation that form the basis (the raw material) for learning will be affected according to our earlier discussion, we can expect the cognitive structures that develop to be different. We can also employ the framework presented to assess the potential forms of (artificial) cognition in robots. Given that robots, in particular humanoid ones, will increasingly move into our everyday lives and we have a strong tendency to project our own ideas onto them, it seems especially important to understand the fundamental differences of their cognitive capabilities due to their entirely different morphologies.

Finally, returning to the computational view of cognition, what is the relation between the evolutionary designs of embodied forms of intelligence (humans and animals) and computational ones such as IBM’s Jeopardy-playing software ‘Watson’ [64]? Morphological computation, by its nature of being implicit in bodily characteristics, does not have to ‘take all potential situations’ into account, so to
speak (which is what makes it so efficient), because they are taken care of ‘automatically’: the spring will simply react to impact without control and the material on the fingertips will deform when a force is applied. In a disembodied computational approach, all potential situations have to be anticipated and rules have to be provided. Most likely, it will depend on the specific task domains whether a purely computational approach can be successful. Good examples are chess and manufacturing environments where (almost) everything can be anticipated.

**Concluding remarks**

Of course, we have not solved the big question of how cognition can be built from the bottom up or how it emerges from body morphology, soft materials, and the interactions of a natural or artificial organism with the world. However, we are beginning to see how the body – the morphological and material properties – and the mind mutually support each other in development, in learning to master a complex body, and in acquiring knowledge about the environment, which allow us better to perform and ultimately survive in the real world. The more you think about it, the more you marvel at how everything fits together and is mutually constitutive of what we call cognition or intelligence: studying one part without taking all of the rest into account does not make sense. Investigating the brain in isolation without taking morphology, materials, and environment into account will only tell us part of the story. It also teaches us very powerful lessons about how to learn from biology and how to build better robots.

**References**

Trends in Cognitive Sciences  xxx xxxx, Vol. xxx, No. x

30  


25 Ida, F. and Ijspeert, A. Biologically inspired robotics. In Handbook of Robotics (Siciliano, B. and Khatib, O., eds), Springer Verlag (in press)  


33 Cliff, D. et al. (1995) Explorations in evolutionary robotics. Adapt. Behav. 2, 73–110  


64 Lally, A. et al. (2012) Question analysis: how Watson reads a clue. IBM J. Res. Dev. 56, 1–14  


73 Martinez, R.V. et al. (2013) Robotic tentacles with three-dimensional mobility based on flexible elastomers. Adv. Mater. 25, 205–212  

74 Nurzaman, S.G. et al. (2013) Active sensing system with in situ adjustable sensor morphology. PLoS ONE 8, e84090  


