Embodied AI as Science: Models of Embodied Cognition, Embodied Models of Cognition, or Both?

Tom Ziemke

University of Skövde, School of Humanities and Informatics,
PO Box 408, 54128 Skövde, Sweden
tom@ida.his.se

Abstract. This paper discusses the identity of embodied AI, i.e. it asks the question exactly what it is that makes AI research *embodied*. From an engineering perspective, it is fairly clear that embodied AI is about robotic, i.e. physically embodied systems. From the scientific perspective of AI as building models of natural cognition or intelligence, however, things are less clear. On the one hand embodied AI seems to be about physically embodied, i.e. robotic models of cognition. On the other hand the term 'embodied' seems to signify the type of intelligence modeled and/or the conception of (embodied) cognition that is underlying the modeling. In either case, it appears that embodied AI, as it currently stands, might be too narrowly conceived since each of these perspectives is addressed only partially.

1 Introduction

"It is not enough to say that the mind is embodied;
One has to say how." [11]

Although more than a decade old now, the above quote summarizes fairly well what this paper is about. It will be argued here that, although, practically by definition, research in embodied AI emphasizes the importance of embodiment for cognitive processes, from a cognitive-scientific perspective it does not take the concept sufficiently seriously. In particular, in our opinion, many researchers, driven by engineering rather than scientific concerns and/or in an attempt to distinguish embodied AI from its traditional predecessor, overemphasize the importance of physical embodiment when it comes to scientific modeling of cognition. Being physical, however, is only one aspect that distinguishes natural embodied cognizers from the computer programs of traditional, cognitivist AI? Hardly surprising therefore, richer conceptions and discussions of embodiment can be found in, other research fields, such as cognitive linguistics and philosophy of mind. Hence, when it comes to embodied AI as cognitive-scientific modeling, it remains unclear, and is hardly ever discussed in the field, what conception of embodied cognition researchers are committed to.

On the one hand, much of embodied AI and its emphasis on physically embodied models is very compatible with the view of robotic functionalism [15], according to which embodiment is about *symbol grounding* or, more generally speaking, *represen-*

tation grounding, whereas cognition/thought can still be conceived of as computation, i.e. syntactically driven internal manipulation of representations. In a nutshell, this is the core and "central research focus" of embodied AI according to a recent review of the field in the *Artificial Intelligence* journal [1], which has subsequently been rejected as too narrow [5]. On the other hand, much of the rhetoric in the field of embodied AI, in particular its rejection of traditional notions of representation, suggests sympathy for more radical notions of embodied cognition that view *all* of cognition as embodied or body-based. This is what in Section 3 will be referred to as the position(s) of "full embodiment" [23] or "radical embodiment" [8]. This paper does not try to argue for one or the other of these views (although it is hardly a secret that we favor the second one), but it simply argues that embodied AI researchers have to realize that there are at least two different views that should not be conflated. Or, to paraphrase and extend the above introductory quote [11]: It is no longer enough for embodied AI researchers to say that (artificial) intelligence has to be embodied; but one has to be more specific concerning what that means.

The rest of this paper is structured as follows. The following section further addresses the problematic identity of embodied AI, i.e. the question what it is that makes it embodied. Section 3 then briefly summarizes different conceptions of embodied cognition and some distinctions that might be useful to import into embodied AI research. Section 4 then discusses the implications for embodied AI as cognitive-scientific modeling.

2 Background: What is *Embodied* AI anyway?

2.1 Motivation

This paper has actually been directly motivated by discussions at and about the Dagstuhl workshop on *Embodied AI*. Mentioning the workshop afterwards to other researchers who had not participated frequently triggered reactions such as *"But, I am working on embodied AI, why didn't I know about this workshop?"* (or *"…, why wasn't I invited?"*) or *"I didn't know there was an embodied AI community"* or *"What the heck is embodied AI?"* or *"Is there any difference between embodied AI and X?"*, where X could be, e.g., (intelligent or cognitive) robotics or (traditional) AI. There are at least two possible explanations for these reactions: (1) what embodied AI is, or is about, is simply not particularly well defined, or (2) it is in fact well defined, but the definition is only well known within a very limited community.

That explanation (1) is at least partly true was also indicated by discussions at the workshop itself, i.e. among the participants who, naturally, as experts might be supposed to have some level of agreement concerning what embodied AI is, and more specifically, exactly what it is that makes it *embodied*. For example, right after a talk that argued that mathematical cognition, although it might seem abstract at a first glance, in fact is embodied in the sense that it is based, more or less directly, on bodily experience, another participant in a discussion argued that the activity of an air traffic controller was situated, but *not* embodied, i.e. that the body was not involved to any significant degree (presumably because there is no, or only little, overt movement involved). The fact that there are different notions of embodiment is hardly surprising in itself. After all, many central terms in the cognitive sciences, such as ‘intelligence’, ‘cognition’, ‘agency’, ‘autonomy’ or ‘life’, are to some degree controversial and still far from being well-defined. What is surprising, however, is that none of the workshop participants reacted (until long after) to either of the above claims, although they are based on diametrically opposed positions, namely that *all* human cognitive processes are embodied or body-based, or that only some of them are, respectively.

This example clearly shows that even within the embodied AI community there are in fact very different conceptions of embodiment, and perhaps consequently embodied AI.[1] As mentioned above, there is not necessarily anything wrong with this - quite the opposite, different conceptual and theoretical frameworks within a field can in many cases lead to fruitful discussions. In the embodied AI community, however, these differences are rarely addressed more than superficially. Fields such as cognitive linguistics, phenomenology and philosophy of mind, on the other hand, seem to take embodiment much more seriously, which has led to richer and more varied conceptions of embodiment as the basis of, for example, meaning and phenomenal experience (e.g. [17, 34, 47]). However, one does not have to look at ‘deep’ philosophical questions to realize that the treatment of embodiment in embodied AI is somewhat shallow.

A more pragmatic problem with embodied AI, or in fact embodied cognitive science in general, is that it seems to be much more defined in terms of what it argues *against*, i.e. traditional AI[2] and the computer metaphor for mind, than what it argues *for* - a fact commonly pointed out by opponents of embodied theories. That means, many embodied AI researchers reject the idea that intelligence and cognition can be explained in purely computational terms, but it is left unclear exactly what the alternative is. Characteristic for the field is, for example, the statement that “intelligence cannot merely exist in the form of an abstract algorithm but requires a physical instantiation, a body” [27]. There are two problems with this: Firstly, being physical can at most be a *necessary* condition for intelligence (which, by the way, is contradicted by some proponents of embodied AI [13, 28]). That means, probably nobody believes that chairs and tables are intelligent, or make better models of intelligence than computer programs for that matter, just because they are physical. Secondly, it is unclear exactly which view concerning (dis-) embodiment this is in opposition to (except for dualism, perhaps). As discussed in more detail elsewhere [6], even proponents of hardcore computationalism would hardly dispute that computer programs require *some* physical instantiation or realization. After all, Newell and Simon, for example, did not include the word ‘physical’ in their *Physical* Symbol Systems Hypothesis [22] for no reason, but they were of course aware of the need for some form of what is now called ‘grounding’ (e.g. [1, 15, 37]), although it perhaps never played a crucial role in their theories.

---

[1] However, most embodied AI researchers, including the author, probably share the intuitive and somewhat unscientific conviction that, as reviewer 1 formulated it, “embodied AI is AI done right, i.e. exploring intelligence and cognition by paying attention to the biological, sensorimotor, evolutionary and developmental bases”.

[2] As reviewer 2 pointed out, what exactly constitutes ‘traditional AI’ is of course equally ill-defined as what constitutes embodied AI, especially since some traditional AI systems, e.g. the robot Shakey, are/were embodied in at least the physical sense (cf. Section 4).

2.2 Embodied AI: Science vs. Engineering

To some extent the somewhat unclear commitment to embodiment seems to arise from the fact that embodied AI has the ambition to combine science and engineering, and that physical embodiment is not equally important in both of them, or at least not important for the same reasons. As several authors have pointed out, AI generally can be viewed from at least two different, though intertwined perspectives: that of *engineering*, mostly concerned with the design of artifacts (robots in the case of embodied AI), and that of *science*, mostly concerned with the understanding of natural systems. Furthermore, the latter can of course be broken down according to the different scientific fields that use robots and/or other autonomous agents as modeling tools, for example, cognitive science (e.g. [2, 25, 27]), neuroscience (e.g. [29, 35]), or the study of animal behavior (e.g. [39, 40]).

While these distinctions appear fairly obvious, they receive surprisingly little attention in discussions of methodology in the field of embodied AI, where overly general statements such as *"simulations are useless"* or *"Khepera robots are not real robots"* or *"existence proofs are not sufficient"* often can be heard. While from an engineering point of view all of these statements might very well be correct, they do not necessarily apply equally generally to the scientific use of autonomous agents as models of natural organisms. Steels, for example, explained the skepticism towards simulations as follows:

> The goal is to build artifacts that are "really" intelligent, that is, intelligent in the physical world, not just intelligent in a virtual world. This makes unavoidable the construction of robotic agents that must sense the environment and can physically act upon the environment, particularly if sensorimotor competences are studied. This is why researchers insist so strongly on the construction of physical agents ... Performing simulations of agents ... is, of course, an extremely valuable aid in exploring and testing out certain mechanisms, the way simulation is heavily used in the design of airplanes. But a simulation of an airplane should not be confused with the airplane itself. [31]

Obviously, Steels had a point there, and nobody would seriously question the view that simulations, however good they are, cannot fully capture the complexities of the physical world. Hence, simulations certainly have limited value in robot engineering. Furthermore, it can very well be argued that physically embodied, robotic systems make better models of animal behavior in cases where a real robot can made to interact with (roughly) the same physical environment as the modeled animal, as in the case of Webb's robot models of cricket phonotaxis [39], which could successfully be tested with real crickets (sounds), or the Pfeifer Lab's Sahabot [19], which was actually tested in the Tunisian desert environments inhabited by the ant species whose navigation behavior it was supposed to model.

However, it is far from clear to what degree this can be generalized to other cases of more general or abstract modeling. Are, for example, Vogt's robotic models of adaptive language games [37], by virtue of their physical embodiment, better scientific models than Steels' partly physical, partly simulated Talking Heads [32] or their fully simulated counterparts [38]? After all, neither the robot bodies used nor their environments in any of the experiments have much of a similarity to their counterparts in human adaptive language games. Although from an engineering point of view the physical models certainly appear more interesting, from a scientific perspective there seems to be no strong reason why they *necessarily* should make better models. Quite the opposite, as argued in more detail elsewhere [44], in many cases simulations, despite their obvious limitations, might have an important, complementary role to play, due to the fact that they allow for more extensive, more systematic and more replicable experimentation, which simply takes less time in simulation, as well as for experiments, e.g. with evolving robot morphologies (e.g. [4]), that can only be carried out in very limited form on real robots.

Just as an aside, concerning the role of existence proofs, one should also distinguish between engineering and scientific modeling. While from an engineering point of view existence proofs certainly are of limited value (e.g. nobody would want to fly in an airplane that has been tested successfully once or twice), from a cognitive science point of view they can be very valuable in the development of theories. Much connectionist cognitive modeling research, for example, has been concerned with providing concrete examples of neural networks exhibiting properties such as systematicity (e.g. [3,14]), which on purely theoretical grounds they had been argued not to be able to exhibit [12]. This is just one example, where existence proofs constrain and thus aid the development of cognitive-scientific theories. For this type of research, both physical and simulated robots, with their respective benefits and drawbacks, are useful tools in agent-based modeling [30], paying more attention to the interaction of agents and environments than traditional computational cognitive modeling of mostly internal processes.

3 Notions of Embodiment

The aim of this section is to briefly overview some distinctions in conceptions of embodiment that might be useful to import into discussion of embodied AI, in particular for the purpose of clarifying differences in theoretical frameworks and commitments in the field that usually remain hidden under a superficial agreement on (physical) 'embodiment'.

Nunez made a useful distinction between trivial, material, and full embodiment [23]. *Trivial embodiment* simply is the view that "cognition and the mind are directly related to the biological structures and processes that sustain them". Obviously, this is not a particularly radical claim, and consequently few cognitive scientists would reject it (dualist philosophers of consciousness, on the other hand, might). According to Nunez, this view further "holds not only that in order to think, speak, perceive, and feel, we need a brain – a properly functioning brain in a body – but also that in order to genuinely understand cognition and the mind, one can't ignore how the nervous system works" [23].

Material embodiment makes a stronger claim, but it is only about the interaction of internal cognitive processes with the environment, i.e. the issue of grounding, and thus considers reference to the body to be only required for accounts of low-level sensorimotor processes In Nunez's terms: "First, it sees cognition as a decentralized phenomenon, and second it takes into account the constraints imposed by the complexity of real-time bodily interactions performed by an agent in a real environment" [23].

Full embodiment, finally, is the view that the body is involved in *all* forms of human cognition, including seemingly abstract activities, such as language or mathematical cognition [18]. In Nunez's own words:

> Full embodiment explicitly develops a paradigm to explain the objects created by the human mind themselves (i.e., concepts, ideas, explanations, forms of logic, theories) in terms of the non-arbitrary bodily-experiences sustained by the peculiarities of brains and bodies. An important feature of this view is that the very objects created by human conceptual structures and understanding (including scientific understanding) are not seen as existing in an transcendental realm, but as being brought forth through specific human bodily grounded processes. [23]

In a similar vein, Clark distinguished between the positions of *simple embodiment* and *radical embodiment* [8]. According to the former, traditional cognitive science can roughly remain the same; i.e. theories are merely constrained, but not essentially changed by embodiment. This is similar to Nunez's view of material embodiment. The position of radical embodiment, on the other hand, very much compatible with Nunez's full embodiment, is, as Clark formulated it, "radically altering the subject matter and theoretical framework of cognitive science" [8].

More recently, Wilson distinguished between six views of embodied cognition [41], of which only the last one requires full or radical embodiment whereas the first five might be considered variations or aspects of material embodiment: (1) cognition is situated i.e. it occurs "in the context of task-relevant inputs and outputs", (2) cognition is time-pressured, (3) cognition is for the control of action, (4) we off-load cognitive work onto the environment, e.g. through epistemic actions [16], i.e. manipulation of the environment 'in the world', rather than 'in the head', (5) the environment is actually part of the cognitive system, e.g. according to Clark and Chalmers' notion of the 'extended mind' [9], and (6) 'off-line' cognition is body-based, which according to Wilson is the "most powerful claim" [41].

Finally, we have elsewhere [6, 43, 45] distinguished between the following views of embodiment and what kind of body it actually requires:

– the view of embodiment as *structural coupling* between agent and environment, which does not necessarily require a physical body (e.g. [10, 13, 24);
– the view of *historical embodiment* as the result of a history of structural coupling and the resulting (mutual) adaptation of an agent to its ecological niche, which again does not necessarily require a physical body (e.g. [28]);
– *physical embodiment*, in the sense discussed above, commonly found in the embodied AI literature;
– *'organismoid' embodiment*, i.e. the view that cognition not only depends on a physical body, but that (organism-like) morphology plays a crucial role, a view also commonly found in embodied AI (e.g. [4, 27]); here we can further distinguish between the claim that the body mediates between internal processes and the environment (e.g. computational properties of materials that substitute of internal processing [26]), which is more in line with material embodiment, and the claim that the key to the embodiment of cognition is the sharing of neural circuitry between sensorimotor and more 'abstract', cognitive processes, which is more in line with full/radical embodiment and Wilson's sixth claim;

– *organismic (or organismal) embodiment*, i.e. the view that at least some aspects of mind (e.g. self and phenomenal experience) crucially depend on the autopoietic, i.e. self-creating and –maintaining, organization of living bodies (e.g. 20, 21, 33, 36, 43, 46, 47).

4 Discussion: Implications for Embodied AI as Science

Raising the question of different conceptions of embodiment in discussions of embodied AI is sometimes dismissed as a philosophical issue of limited value to the practice of embodied AI research. It should be noted, however, that the questions raised in this paper, although they overlap with philosophical issues, are not themselves questions of philosophy, but questions of scientific methodology and practice, i.e. the kind of questions that any scientific community has to ask itself, e.g. what defines and sustains a field as such, and the need for shared conceptions and agreed-upon terminology.

It has been pointed out in this paper that the identity of embodied AI, i.e. what it is that makes a particular type of AI research (or several, in this case) ‘embodied’, is far from clear. As mentioned before, from an engineering perspective, it seems fairly obvious that embodied AI is about robotic, i.e. physically embodied systems. From the scientific perspective of AI as building models of natural cognition or intelligence, however, things are less clear.

On the one hand embodied AI seems to be about physically embodied, i.e. robotic models of cognition. This matches the engineering perspective very well, and it allows us to distinguish the approach of embodied AI from its traditional, cognitivist counterpart which predominantly used computer programs as models of cognition. However, if physical, robotic models of cognition is what embodied AI is about then one might ask why there is very little interaction between embodied AI research and the work of the type carried out, for example, in Reiter’s *Cognitive Robotics Group* at the University of Toronto[3] which uses traditional, symbolic AI techniques, such as situation calculus, in real robotic systems, i.e. carrying on the type of AI that started with Stanford’s Shakey project in the 1960s. It seems quite obvious that, despite the use of physically embodied robots, not many embodied AI researchers would consider this an example of embodied AI. In fact the type of symbolic knowledge representation used in this type of AI is rejected outright by many proponents of embodied AI. The use of physically embodied robots then, after all, does not, at least not by itself, seem to be a distinguishing feature of embodied AI.

On the other hand, for many embodied AI researchers, the term *embodied* seems to signify the conception of (embodied) cognition that is underlying their work. This then supposedly is the reason why the work of Reiter’s group, for example, would not count as embodied AI, because it supposedly is not based on a theoretical framework that conceives of cognition as embodied. However, this is not unproblematic either, since, as discussed in the previous section, in some sense(s) the work of Reiter’s group could very well be characterized as guided by the notions of simple, trivial or

[3] For details see http://www.cs.toronto.edu/cogrobo/.

material embodiment. Is then perhaps the conception of radical or full embodiment, i.e. the view that all of cognition is embodied or body-based, what distinguishes embodied AI from non-embodied AI? Well, this does not seem to match the practice of embodied AI very well, as discussed above, since clearly not everybody in the field, perhaps not even a majority, would subscribe to a fully or radically embodied view of cognition, as previously illustrated by the case of air traffic control. Furthermore, if embodied AI was actually dedicated to building models of fully/radically embodied cognition, the community would have to ask itself why it has so little interaction with work of the type carried out by, for example, Lakoff, Feldman and Shastri's *Neural Theory of Language* group at Berkeley[4] that builds neuro-computational models of embodied cognition, in the full/radical sense, but sees no need for physically embodied, robotic models. Is this not embodied AI, because it deals with non-embodied models?

Since neither the use of physically embodied models nor the modeling of embodied theories of cognition seems to properly characterize the identity of embodied AI as cognitive-scientific modeling, one might ask if perhaps it is the combination of the two? That means, one might want to characterize embodied AI as the use of (physically) embodied systems in the modeling of embodied theories of cognition. But again, both of these would require a substantial re-definition of what we consider embodied AI today, because, as discussed above, either you use a simple conception of embodiment and thereby include robotically-grounded-symbol-systems-type AI, which clearly is incompatible with current mainstream embodied AI, or you use the conception of radical/full embodiment as a theoretical framework, which would exclude much of what is currently considered embodied AI.

Finally, embodied AI does of course not necessarily have to adopt any coherent definition or theoretical framework, but can continue as the pluralistic research field that it currently is, addressing to some degree both computational and physically embodied models of both non-embodied and embodied theories of cognition. However, this runs risk of confirming the old criticism that embodied AI is defined only in terms of what it is *against* (traditional AI, which itself is not well-defined either), rather than what it is *about*, and it might in fact be worth considering to further open up the field for research that is currently not considered embodied AI. Whatever the future of the field, embodied AI as a scientific endeavor would certainly benefit from further clarification of its own theoretical foundations and commitments.

Acknowledgements

The author would like to thank Rafael Nunez since many of the points raised in this paper stem from discussions with him in Dagstuhl. Collaboration with Ron Chrisley and Jessica Lindblom also helped to clarify some of the issues involved. Thanks also to the anonymous reviewers who provided useful feedback on the first version of this paper.

[4] For details see http://www.icsi.berkeley.edu/NTL/.

References

1. Anderson, M. (2003). Embodied Cognition: A Field Guide. *Artificial Intelligence*, 149(1), 91-130.
2. Berthouze, L. & Ziemke, T. (2003). Epigenetic Robotics: Modelling Cognitive Development in Robotic Systems. *Connection Science*, 15(4), 147-150.
3. Bodén, M. & Niklasson L. (2000). Semantic systematicity and context in connectionist networks, *Connection Science*, 12(2), 1–31.
4. Buason, G.; Bergfeldt, N. & Ziemke, T. (in press). Brains, Bodies, and Beyond: Competitive Co-Evolution of Robot Controllers, Morphologies and Environments. *Genetic Programming and Evolvable Machines*, to appear.
5. Chrisley, R. (2003). Embodied Artificial Intelligence. *Artificial Intelligence*, 149(1), 131-150.
6. Chrisley, R. & Ziemke, T. (2002). Embodiment. In: *Encyclopedia of Cognitive Science* (pp. 1102-1108). London: Macmillan Publishers.
7. Clark, A. (1997). *Being There*. Cambridge, MA: MIT Press.
8. Clark, A. (1999). An embodied cognitive science? *Trends in Cognitive Science*, 9, 345-351.
9. Clark, A. & Chalmers, D. (1998).The Extended Mind. *Analysis* 58 (1), 7-19.
10. Dautenhahn, K.; Ogden, B. & Quick, T. (2002). From embodied to socially embedded agents. *Cognitive Systems Research*, 3(3), 397-428.
11. Edelman, G. (1992). *Bright Air, Brilliant Fire: On the Matter of the Mind*. Penguin.
12. Fodor, J. & Pylyshyn, Z. (1988). Connectionism and cognitive architecture: A critical analysis. *Cognition*, 28, 3-71.
13. Franklin, S. A. (1997). Autonomous agents as embodied AI. *Cybernetics and Systems*, 28(6), 499-520.
14. Hadley, R.F; Rotaru-Varga, A.; Arnold, D.V. & Cardei, V.C. (2001). Syntactic systematicity arising from semantic predictions in a Hebbian-competitive network. *Connection Science*, 13(1), 73-94.
15. Harnad, S. (1989). Minds, Machines and Searle. *Journal of Theoretical and Experimental Artificial Intelligence*, 1(1), 5-25.
16. Kirsh, D., & Maglio, P. (1994). On distinguishing epistemic from pragmatic action. *Cognitive Science*. 18, 513-549.
17. Lakoff, G. & Johnson, M. (1999). *Philosophy in the Flesh*. New York: Basic Books.
18. Lakoff, G. & Nunez, R. (1999). *Where Mathematics Comes From*. New York: Basic Books.
19. Lambrinos, D.; Marinus, M.; Kobayashi, H.; Labhart, T.; Pfeifer, R. & Wehner, R. (1997). An autonomous agent navigating with a polarized light compass. *Adaptive Behavior*, 6(1):131-161.
20. Maturana, H. R. & Varela, F. J. (1980). *Autopoiesis and Cognition*. Dordrecht: Reidel.
21. Maturana, H. R. & Varela, F. J. (1987). *The Tree of Knowledge - The Biological Roots of Human Understanding*. Boston, MA: Shambhala.
22. Newell, A. & Simon, H. (1976). Computer Science as Empirical Inquiry: Symbols and Search. *Communications of the ACM*, 19, 113-126.
23. Nunez, R. (1999). Could the Future Taste Purple? Reclaiming Mind, Body and Cognition. *Journal of Consciousness Studies*, 6(11-12), 41-60.
24. Quick, T.; Dautenhahn, K.; Nehaniv, C. & Roberts, G. (1999). On Bots and Bacteria: Ontology Independent Embodiment. In: Floreano, D. et al. (eds.) *Proceedings of the Fifth European Conference on Artificial Life*. Heidelberg: Springer Verlag.
25. Pfeifer, R. (1995). Cognition – Perspectives from autonomous agents. *Robotics and Autonomous Systems*, 15, 47-70.

26. Pfeifer, R. (2000). On the role of morphology and materials in adaptive behavior. In: Meyer, J.A.; Berthoz, A.; Floreano, D.; Roitblat, H. & Wilson, S.W. (eds.) *From animals to animats6* (pp. 23-32). Cambridge, MA: MIT Press.
27. Pfeifer, R. & Scheier, C. (1999). *Understanding Intelligence*. Cambridge, MA: MIT Press.
28. Riegler, A. (2002). When is a Cognitive System Embodied? *Cognitive Systems Research*, 3(3), 339-348.
29. Ruppin, E. (2002). Evolutionary autonomous agents: A neuroscience perspective. *Nature Reviews Neuroscience*, 3(2), 132-142.
30. Schlesinger, M. & Parisi, D. (2001). The agent-based approach: A new direction for computational models of development. *Developmental Review*, 21, 121-146.
31. Steels, L. (1994). The artificial life roots of artificial intelligence. *Artificial Life*, 1, 75-110.
32. Steels, L. (1999). *The Talking Heads Experiment*. Antwerpen: Laboratorium.
33. Stewart, J. (1996). Cognition = Life: Implications for higher-level cognition. *Behavioral Processes*, 35, 311-326.
34. Varela, F. J.; Thompson, E. & Rosch, E. (1991). *The Embodied Mind*. Cambridge, MA: MIT Press.
35. Voegtlin, T. & Verschure, P. (1999). What can robots tell us about brains? *Reviews in Neuroscience*, 10(3-4), 291-310.
36. von Uexküll, J. (1982). The Theory of Meaning. *Semiotica*, 42(1), 25-82.
37. Vogt, P. (2002). The physical symbol grounding problem. *Cognitive Systems Research*, 3(3) 429-457.
38. Vogt, P. (2003). THSim v3.2: The Talking Heads simulation tool In: Banzhaf, W.; Christaller, T.; Dittrich, P. & Kim, J.T & Ziegler, J. (eds.) *Advances in Artificial Life - Proceedings of the 7th European Conference on Artificial* Life. Heidelberg: Springer.
39. Webb, B. (2000). What does robotics offer animal behaviour? *Animal Behavior*, 60, 545-558.
40. Webb, B. (2001). Can robots make good models of biological behaviour? *Behavioral and Brain Sciences*, 24(6).
41. Wilson, M. (2002). Six views of embodied cognition. *Psychonomic Bulletin and Review*, 9(4), 625-636.
42. Ziemke, T. (2001). The Construction of 'Reality' in the Robot. *Foundations of Science*, 6(1), 163-233.
43. Ziemke, T. (2001). Are Robots Embodied?. In: Balkenius, C.; Zlatev, J.; Brezeal, C.; Dautenhahn, K. & Kozima, H. (eds.) *Proceedings of the First International Workshop on Epigenetic Robotics: Modelling Cognitive Development in Robotic Systems* (pp. 75-83). Lund University Cognitive Studies, vol. 85, Lund, Sweden.
44. Ziemke, T. (2003). On the Role of Robot Simulations in Embodied Cognitive Science. *AISB Journal*, 1(4), 389-399.
45. Ziemke, T. (2003). What's that thing called embodiment? In: Alterman, R. & Kirsh, D. (eds.) *Proceedings of the 25th Annual Conference of the Cognitive Science Society* (pp. 1305-1310). Mahwah, NJ: Lawrence Erlbaum.
46. Ziemke, T. & Sharkey, N. E. (2001). A stroll through the worlds of robots and animals. *Semiotica*, 134(1-4), 701-746.
47. Zlatev, J. (2002). Meaning = Life (+ Culture) - An outline of a unified biocultural theory of meaning. *Evolution of Communication*, 4 (2), 175-199.