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Humanoid Theory Grounding

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Abstract

In this paper we consider the importance of using a humanoid physical form for a certain proposed kind of robotics, that of theory grounding. Theory grounding involves grounding the theory skills and knowledge of an embodied artificially intelligent (AI) system by developing theory skills and knowledge from the bottom up. Theory grounding can potentially occur in a variety of domains, and the particular domain considered here is that of language. Language is taken to be another “problem space” in which a system can explore and discover solutions. We argue that because theory grounding necessitates robots experiencing domain information, certain behavioral-form aspects, such as abilities to socially smile, point, follow gaze, and generate manual gestures, are necessary for robots grounding a humanoid theory of language.

Introduction

It is easy to forget that theories are intimately connected with the world. Technical descriptions of theories can be found in books and papers, which are by virtue of media separated from the world. Words, diagrams, and tables of numbers only at best indirectly interact with the world. Perhaps it is partially for these reasons that some artificial intelligence (AI) efforts at incorporating theory into AI systems have separated their AI programs from the world. For example, the *IOU* machine learning system of [1] has inputs of a propositional (Horn-clause) concept definition, feature-based concept examples, and a propositional domain theory, and outputs a specialization of the input concept consistent with the examples. In this machine learning approach, the theory does not interact directly with the environment. For related work, see also [2] and [3].

An alternative for AI systems is to intimately connect their theories with the world using *theory grounding* [4]. Theory grounding uses the metaphor of human theory development as its guiding approach. Humans acquire theories through semi-autonomous processes of interaction with the world.

Some theories are learned through linguistic-based study (e.g., reading), some theories are taught to us by others in a more tutorial fashion, and some theories, perhaps our less formal ones, are acquired by direct experience with the physical and social world. In this paper, we take it to be vital to the character of a theory that it be learned and developed through interaction with the world. We are most interested in the world, so it makes sense for our theories to be directly connected to, and about, the world.

In this paper we start to add a next level of theorizing to the concept of theory grounding. By itself, theory grounding certainly does not sufficiently constrain the problem of robotic modeling. We start to narrow the problem by considering the domain of language. That is, we consider issues relating to a robotic system learning and developing a *theory of language*. Considering a robotic system developing a theory of language leads us to analyzing the types of sensori-motor scheme, body morphology, and environment that may eventually lead to successfully constructing robotic systems that develop a theory of language. Our specific focus in considering sensori-motor schemes, body morphology, and environment is analyzing the importance of using a humanoid form for this theory grounding.

The remainder of this paper is arranged in the following manner. First, we provide more details on the proposal of theory grounding, giving theoretical and practical rationales for this principle. Second, we introduce the concept of a theory grounded theory of language. As it is atypical to consider language acquisition from a view of theory learning, we spend some time developing this idea. Next, given this background, we analyze the importance of using a humanoid form in actual theory grounded robotic systems in the area of theory of language.

Theory Grounding

Theory grounding is an extension of the concept of symbol grounding [5] in that a central tenet of symbol grounding is to causally connect the parts of an AI program with the world. What differs in theory grounding is the nature of the parts being grounded,

and the ensuing details. Instead of proposing that the symbols of AI programs be grounded, we propose instead that theoretical structure be grounded. Further, since theories are dynamic as opposed to being comprised of temporally isolated, static representations and skills, theory grounding needs to capture this dynamic quality. To this end, in order that a grounded theory assimilates and accommodates additional information, data, examples, etc., we propose that theories should also be semi-autonomously learned or *developed* by the embodied AI system. While symbols in symbol grounded systems may conceivably be static and unchanging, theories naturally undergo processes of change (e.g., see [6]), and so theory grounding needs to account for this change.

There are both practical and theoretical reasons to strive towards the goal of theory grounded embodied AI. Practically, it seems evident that while learning techniques based on statistical properties of the input data ([7], [8], [9]) can produce good results in some situations, there is room for improvement in the generalizations made by artificially intelligent systems. Theory grounding may be able to assist our embodied AI systems in much the same way as theories assist us as humans—that is, by reducing the set of hypotheses in the search space, and hence enabling principled predictions about social interactions, physical situations, and action outcomes. In short, theory grounding shows promise for enhancing generalization.

Theoretically, theory grounding also has interesting possibilities. [10] and [11] have observed that symbol grounding (and its robotic counterpart, *physical grounding* [12]) has not yet resolved the cognitive science issues of conceptual representation, productivity, and systematicity. Productivity and systematicity are properties of certain representational systems. Productivity is the property of a representational system being able to encode indefinitely many propositions. Systematicity is the property of a representational system being able to represent the relation bRa given that the system can represent the relation aRb ([13]). At least in retrospect, the relative lack of research progress on these topics based on the starting point of symbol grounding is not surprising. First, while the properties of productivity and systematicity have been taken to be related to symbolic representation ([13]), there is little offered guidance regarding *how* to proceed towards productivity and systematicity given the concept of symbol grounding. Second, given the variation in contemporary usage of the term “symbol”, the kinds of grounding that may be achieved likely thus have variation. For example, [14] and [15] relate the term “symbol” to information

processing performed by pigeons in specific kinds of operant conditioning tasks. Grounding symbols as per the information processing of pigeon psychology may likely provide very different outcomes than grounding symbols in a manner similar to the information processing of human psychology.

The proposal we make (see also [4]) is that while symbol grounding has brought us to the beginning of the road, theory grounding can help pave the way to more progress on issues of conceptual representation, productivity, and systematicity, precisely because these properties arise as a consequence of the theoretical structure of the system. That is, we claim that these properties arise as a consequence of the skills and knowledge that a system has for acquiring, processing, and representing theory. We suggest that theoretical structures enable the processing and representation of structures related to infinite competence ([16]). Infinite competence and productivity are similar ideas in that they both pertain to the apparently unlimited content that can be represented by the systems of interest. This brings us to a theoretical faltering point. Any finite system will have finite performance limits. How do we resolve the facts of finite performance and infinite competence? What does infinite competence really mean? We suggest that instead of phrasing these issues in terms of infinite competence, we need to talk about *concepts* of infinity, and imbuing an AI system with concepts of infinity. It seems entirely reasonable for a system to have finite performance limits, and yet also have *concepts* related to objects or events of infinite duration or size. The indefinitely large number of propositions encoded in a system with the property of productivity may be directly related to that system possessing concepts of infinity. Such systems (and humans are our present example) are not just in principle capable of infinite competence, rather they are in practice capable of representing concepts of infinity.

Our point here has been that if productivity and systematicity (and we hold out for conceptual representation more generally as well), are in fact based in concepts arising from the theoretical structure of a system, then theory grounding seems a plausible way to achieve these properties. At a minimum, this is an approach that provides guidance towards these representational properties. That is, as we’ll see in the next section, our proposal for theory grounding involves patterning the developments in embodied AI after the cognitive and linguistic developments of young infants and children.

Theory Grounded Theory of Language

Humans learn and develop their skills and knowledge with theories from infancy, and beyond. As adults,

we may come to acquire various specific theories, some of them formal, some of them informal. One area of naïve theory skill and knowledge that has been extensively studied is the area of social understanding known as *theory of mind* (e.g., see [17]). The idea here is that we as humans come to think of our cohorts as having mental states, such as attention, and “our naïve understanding of mind, our mentalistic psychology, is a theory. It is a naïve theory but not unlike a scientific theory” (p. 2, [18]).

Theory grounding, with its emphasis on a bottom-up connection of theory to the world, suggests patterning the learning and development of theory after human infants and children. For example, one development that comes into play relatively early and appears related to theory of mind is that of the animate vs. inanimate distinction ([19]). Presumably, since they are developing naïve theories about particular kinds of entities, i.e., those with minds, infants need to make basic distinctions between animate (e.g., objects with minds) and inanimate objects.

Our specific area of concern in this paper is theory of language. That is, a theory grounded theory of language. Before we turn to describing just what we mean by this, given that viewing language as a theory is somewhat unusual, we first indicate our rationale for focusing on language. Language seems a particularly promising area in which to investigate theory grounding because while we could choose to have our robotic systems develop theories of the inanimate physical world, or conversely, develop theories of the animate social world, the intersection of the physical and social worlds seems the most promising. This intersection seems the most promising because in order to properly describe the physical world, one has to include the social world: Agents (e.g., humans) interact with objects. Additionally, in order to properly describe the social world, one has to also describe the physical world. Social beings interact with objects. Given these starting points, the area of language seems a natural venue within which to explore theory grounded robotic systems, because acquiring language skills requires knowledge of both the social world (e.g., people are the agents of linguistic communication), and of the physical world (e.g., we often use language to talk about the physical world). Additionally, it seems very likely that theory and language are intimately related, and perhaps even in the early developmental stages of children (e.g., [20]).

How then can language be viewed as a theory? First, it has been argued that human natural language cannot be acquired strictly by learning (i.e., inductively; [21]). If this is the case, and language is

also not strictly genetically encoded in humans (i.e., innate; [22]), then an alternative way in which language may be acquired is through use of a theory of language to bias the incoming input linguistic stream. For example it may be on the basis of a theoretical insight that infants come to “infer ... that all objects, salient or not, significant or not, have a name to be discovered” (p. 194, [6]). Second, words, concepts, and theories seem intrinsically related. “Words ... [are] linked to one another in a coherent, theoretical way, and appreciating these links is part of understanding [a] theory” (p. 195, [6]). Third, a key issue in theory building is that of representation. Language provides a media, namely, words, that enable concepts to be structured and hypotheses to be formulated. This last issue, it should be acknowledged, is less about language as a theory, and more about language as a meta-theory (or *theory theory*; see [6]).

So, we enter into the realm of language acquisition thinking of the child as actively engaged in the process of acquiring language as a theory, and also not viewing language as particularly different than any other problem space ([23]), or domain of theory to be learned, and developed. In some sense then, by divesting language of at least some “special” properties, this should render the problem more amenable to computational and robotic investigation.

Focusing our concerns further, in our particular project, we are utilizing the developmental psycholinguistic theory proposed by [24]. This theory relates to children’s initial learning of words and is termed an *emergentist coalition* theory of word learning. This theory has been tested in the context of an empirical method for measuring a child’s word learning through comprehension and specifically, through measurements of the child’s looking time. In this method, the child is seated in her mother’s lap, and the experimenter verbally labels one of two differing toys with a novel label (e.g., “This is a *glorp*”). In a testing phase, the child sees the two toys presented side by side, and the (hidden) experimenter requests the target object. Presumably, children who have learned the label for the target object will tend to look longer at the target object.

The emergentist coalition theory posits that children use a range of cue or information types in learning words: Attentional cues, social cues, and linguistic cues. Attentional cues involve information comprising the “earliest influences on word learning ... such as perceptual salience, temporal contiguity, and novelty” (p. 18, [24]). Social cues include eye gaze and pointing. Linguistic cues “are cues from the language input itself, which help infants to find the words in the speech stream and identify their part of speech” (p. 20, [24]). For example, the difference

between the mother's speech sounds and the sounds made by animals, the child's crib toy, and the beep of a microwave oven. The emergentist coalition theory hypothesizes that each of these types of cues are perceptually available to the child from the start of word learning, but that children differentially utilize the cues in their cognitive skills of learning words, over the course of development. For example, while a nine-month-old can perceptually recognize aspects of the eye gaze of an adult ([25]), they don't start to cognitively utilize adult eye-gaze as a social cue in word learning until about 12 months of age ([24]). "Children may come to realize, pragmatically, that eye gaze is a good indicator of the consistent mapping [of words to objects], and they may come to follow it, or make use of it in directing attention" (p. 25, [24]). The authors of this theory refer to such mechanisms (i.e., involved in the causal assessment of the utility of eye gaze in learning words) as "guided distributional learning." This ties in directly to the present view of a theory of language. The children are viewed as evaluating and weighing the kinds of cues that can be used to best inform the word learning process. The social cue of eye gaze comes to be selected as a relevant piece of information precisely because of its occurrence in the linguistic environment. Of course, at the time the child is learning his or her first "words", these words may be less linguistic and more rote in their basis [26], [27]). A child just doesn't have as a goal: "I need to learn the cues that best serve me learning words." Rather, in the present view, the child is using an implicit and naïve theoretical vantage to make causal sense out of the world (see also [28]). Words just happen to make up a substantial portion of a child's world, and so the child formulates a naïve theory of language including the ideas that objects have names, and that eye gaze is an important cue to figure out which word goes with which object or class of objects.

Humanoid Theory Grounding

We are approaching language and theory of language because of our interests in theory grounding, and because there is a well established collection of data, ideas, and theory in this area (i.e., child language development). Because language is human¹, it seems reasonable to consider the importance of using a humanoid robot in this endeavor. We consider the following issues: (1) providing the robotic system with an appropriate environment, (2) body

¹ While we applaud (and one of us has been involved in) animal language research, it is still at best controversial as to whether other animals can possess language comprehension skills past that of a two-year-old human child, and even then the animals' skills have facets markedly different than those of the child ([29], [30], [31]).

morphology and sensori-motor systems in terms of properly grounding the theory of language, and (3) the potential for modeling variations in language development.

Environment Issues

A robot acquiring a theory grounded theory of language (we'll abbreviate this to just "theory of language" in the following) will need to have an environment that makes it possible for it to acquire the theory of language. Just as humans must have a language environment in order to acquire language, a robot acquiring a theory of language will also need a language environment. As children tacitly "rely on adults to provide reasonably good linguistic information most of the time" (p. 209, [6]), so will theory grounded robots depend on their humans to provide a quality linguistic environment. An important point here is that while practical natural language processing systems may be designed to immediately allow a user to verbally interact with a computer system (e.g., to perform domain restricted queries on a database), a theory of language robotic system will be relatively incompetent (in it's "infancy") for a period of time. The design of these systems, when and if we are able to construct them will, by their patterning on human development, have them start with very little knowledge and skills and gradually, through environmental interaction, learn and develop their knowledge and skills. A question in terms of environment is: How will we motivate the humans that interact with these robots to persist in their interactions over the course of time that the robot is developing its theory of language? Further, the humans that interact with these robots will be of varying ages and backgrounds. Practically, these robots will enter at least some of our homes because of this need for an ongoing linguistic environment. At that point, the need for motivating an entire family, comprising individuals of varying ages and backgrounds will be firmly present.

It seems clear that various ergonomic, user interface, and aesthetic issues will come into play in the physical design of the robot, in order to stimulate a variety of people to interact with it. Of course, during this "infancy" period, it is most important that at least some people interact with the system, e.g., perhaps the primary caregiver of the system. Human children, over evolutionary time, have developed finely honed strategies that help them to acquire various resources from their caregivers (see [32]). For example, children from about two-months-of-age start to exhibit social smiling and this smiling is positively motivating for caregivers (e.g., [33]). One result of these strategies is to help ensure a proper linguistic environment for the child. From our view then, the approach taken by [34] with their robot KISMET, which shows some analogs of human

facial emotional features, is the right direction to proceed to motivate individuals, and especially primary caregivers, to interact with robots developing a theory of language. Motivating humans in the robots' environment to interact linguistically, and provide "reasonably good linguistic information most of the time" will undoubtedly also have other features. A full humanoid form may not be necessary or beneficial in terms of motivating the humans in the linguistic environment, but some features (e.g., smiling) would seem to be crucial.

[35] also emphasize the importance of environmental issues, and suggest robots will have a problem encountering new environments in terms of defining the complexity of the unseen environment. Our proposed solution to this problem is to have the robot start in an infancy-mode. That is, the robot will initially assume a reduced environmental complexity, provided to it by its environment providers ("caregivers").

Body Morphology and Sensori-Motor Systems

Certain humanoid features of the robotic system would seem important in learning and developing a theory of language, and particularly so because of our approach of theory grounding. We suggest that in order to properly acquire aspects of a theory, the robot will have to have experiences with those aspects. For example, the language-related behaviors of gaze following and pointing rely on particular body morphology and sensori-motor systems. Gaze following, the skill of tracking another's gaze (e.g., [25]), requires active vision, and the robot's motor system will need to be sufficiently mobile that it enables following a range of another's gaze. Pointing is an example more directly tied to language—the human gesture of pointing is often taken as referential. In order for the robot to express itself via pointing, it will likely need some kind of arm-like pointing device.

Our point here is that in order to properly ground a theory of language, a robot will need to have at least some features of a humanoid form. We propose that theory grounding will only take place with those physical aspects that the robot can directly experience. Thus, in order to develop a theory of language that encompasses reference via gaze following and pointing, the robot will need to have the relevant body and sensori-motor features. If the robot is lacking these body and sensori-motor features, then this will reduce the theory of language developed by the robot, and we expect, similarly reduce the common ground that we can share with the robot.

Modeling Variations in Language Development

One goal we have in establishing a robot with a theory of language is to provide a robotic and

computational model of language development in children, to act as a predictive tool in empirical studies with children (e.g., see [36]; more generally see [37]). With this in mind, and with our theory grounding assumptions, it makes sense for us to design our robots with a reasonably humanoid form. In this way, the robots should develop a theory of language closer to that acquired by humans, and thus we will have a model system that more closely approximates human linguistic development.

Such a system should enable us to not only generate predictions of language experiments to be conducted with human children, but also to explore variations in language development. We will be able to alter initial mechanisms of the robotic system congruent with hypotheses about the pathways for these variations in development, and then test the robotic system to determine if it shows features similar to those expressed in the specific area. For example, [38] have hypothesized that problems in a sensori-motor system related to the abstract representation of goal directed behaviors ("mirror neurons") results in autism, which is a language-related disorder (see also [39]). If our robotic model includes such systems of sensori-motor abstraction, along with other necessary mechanisms, we should be able to provide an evaluation of their hypothesis. We should also be able to model the outcomes of other and less severe variations from normal language development as well, such as what happens when normal acoustic input is denied to the system. We would expect a robot developing a theory of language to develop a theory even if the input/output modality is manual and not spoken. That is, it should be possible for the system to acquire a sign-based language (e.g., [40]). Of course, specific humanoid morphology would be required in order for the robot to articulate manual gestures.

Conclusions

If we want a robot to develop a human-type theory, then it seems likely that we will need a human-type robotic form. Or, in present terms: To get a humanoid theory, we need a humanoid robot. This relation follows from the assumptions of theory grounding. Theory grounding indicates that in order for a robot to properly learn and develop a theory, it needs experience with the relevant aspects of the sensori-motor environment. Since, there are aspects of the sensori-motor environment that are pertinent to our example of grounding a theory of language (e.g., gaze following, pointing), we suggest that at least a basic humanoid form will be required to properly ground a theory of language.

It seems clear that having a humanoid robot (as opposed to having a dog or dolphin robot, for example) develop a theory of language will have various practical and useful outcomes. Not only will

the acquisition of the theory of language be facilitated by motivating individuals to provide reasonable language inputs (e.g., the robot will socially smile), but a broader linguistic common ground should be established by having the robot develop concepts related to those of humans (e.g., a concept of reference via pointing). Additionally, if the robot develops a relatively human-like theory of language, this should provide opportunities for modeling variations in language development, and hence provide practical outcomes in terms of increasing our understanding of these processes of development.

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References

- [1] Mooney, R. J. (1993). Integrating theory and data in category learning. In: G. Nakamura, R. Taraban, & D. L. Medin (Eds.), *Categorization by Humans and Machines: The Psychology of Learning and Motivation*, Vol. 29 (pp. 189-218). Orlando, FL: Academic Press.
- [2] Mitchell, T. M., Keller, R., & Kedar-Cabelli, S. (1986). Explanation-based generalization: A unifying view. *Machine Learning*, 1, 47-80.
- [3] McIlraith, S. & Amir, E. (2001). Theorem proving with structured theories. Paper presented at the *Seventeenth International Joint Conference on Artificial Intelligence*, August 4-10, Seattle, WA.
- [4] Prince, C. G. (2001). Theory grounding in embodied artificially intelligent systems. Paper presented at *The First International Workshop on Epigenetic Robotics: Modeling Cognitive Development in Robotic Systems*, held Sept 17-18, 2001, in Lund, Sweden.
- [5] Harnad, S. (1990). The symbol grounding problem. *Physica D*, 42, 335-346.
- [6] Gopnik, A. & Meltzoff, A. N. (1997). *Words, Thoughts, and Theories*. Cambridge, MA: MIT Press.
- [7] Ballard, D. H. (1997). *An Introduction to Natural Computation*. Cambridge, MA: MIT Press.
- [8] Elman, J. (1998). Generalization, simple recurrent networks, and the emergence of structure. In M. A. Gernsbacher & S. Derry (Eds.), *Proceedings of the 20th Annual Conference of the Cognitive Science Society*. Mahway, NJ: Lawrence Erlbaum Assoc.
- [9] Hertz, J., Krogh, A., & Palmer, R. G. (1991). *Introduction to the Theory of Neural Computation*. Lecture Notes Volume I. Santa Fe Institute Studies in the Science of Complexity. Reading, MA: Perseus Books.
- [10] Kirsh, D. (1991). Today the earwig, tomorrow man? *Artificial Intelligence*, 47, 161-184.
- [11] MacDorman, K. F. (1999). Grounding symbols through sensorimotor integration. *Journal of the Robotics Society of Japan*, 17, 20-24.
- [12] Brooks, R. A. (1999). *Cambrian Intelligence: The Early History of the New AI*. Cambridge, MA: MIT Press.
- [13] Fodor, J. A. & Pylyshyn, Z. W. (1988). Connectionism and cognitive architecture: A critical analysis. *Cognition*, 28, 3-71.
- [14] Gallistel, C. R. (2001). *The Symbolic Foundations of Conditioned Behavior*. Colloquium given at University of Minnesota, Minneapolis, MN on May 11, 2001.
- [15] Gallistel, C. R. & Gibbon, J. (2000). Time, rate, and conditioning. *Psychological Review*, 107, 289-344.
- [16] Chomsky, N. (1968). *Language and Mind*. New York: Harcourt, Brace and World.
- [17] Flavell, J. H. (2000). Development of children's knowledge about the mental world. *International Journal of Behavioral Development*, 24, 15-23.
- [18] Wellman, H. M. (1990). *The Child's Theory of Mind*. Cambridge, MA: MIT Press.
- [19] Rakison, D. H. & Poulin-Dubois, D. (2001). Developmental origin of the animate-inanimate distinction. *Psychological Bulletin*, 127, 209-228.
- [20] Astington, J. W. & Jenkins, J. M. (1999). A longitudinal study of the relation between language and theory of mind development. *Developmental Psychology*, 35, 1311-1320.
- [21] Gold, E. M. (1967). Language identification in the limit. *Information and Control*, 10, 447-474.
- [22] Pinker, S. (1994). *The Language Instinct*. New York: William Morrow.
- [23] Karmiloff-Smith, A. (1979). *A Functional Approach to Language: A Study of Determiners and Reference*. New York: Cambridge University Press.
- [24] Hollich, G. J., Hirsh-Pasek, K., & Golinkoff, R. M. (2000). Breaking the language barrier: An emergentist coalition model for the origins of language learning. *Monographs of the Society for Research in Child Development*, Serial No. 262, Vol. 65, No. 3.

- [25] Butterworth, G. & Jarrett, N. (1991). What minds have in common is space: Spatial mechanisms serving joint visual attention in infancy. *British Journal of Developmental Psychology*, 9, 55-72.
- [26] Hennon, E. A., Slutzky, C. B., Sootsman, J., Hirsh-Pasek, K., & Golinkoff, R. M. (2001). Reconciling competing theories of word learning: Developmental changes from 10 to 24 months. Poster presented at the *Biennial Meeting of the Society for Research in Child Development*, April 2001, Minneapolis, MN.
- [27] Hirsh-Pasek, K., Golinkoff, R. M., & Hennon, E. A. (submitted). The birth of words.
- [28] Povinelli, D. J. & O'Neill, D. A. (2000). Do chimpanzees use their gestures to instruct each other? In: S. Baron-Cohen, H. Tager-Flusberg, & D. J. Cohen (Eds.), *Understanding Other Minds: Perspectives From Autism*, Second Edition (pp. 459-487). Oxford: Oxford University Press.
- [29] Kako, E. (1999). Elements of syntax in the systems of three language-trained animals. *Animal Learning & Behavior*, 27, 1-14.
- [30] Prince, C. G. (1993). *Conjunctive Rule Comprehension in a Bottlenosed Dolphin*. Unpublished Masters Thesis, University of Hawaii Manoa.
- [31] Savage-Rumbaugh, E. S., Murphy, J., Sevcik, R. A., Brakke, K. E., Williams, S. L., & Rumbaugh, D. M. (1993). Language comprehension in ape and child. *Monographs of the Society for Research in Child Development*, Serial No. 233, Vol. 58.
- [32] Povinelli, D. J. & Prince, C. G. (in preparation). Parental-offspring conflict and the development of social understanding.
- [33] Wolff, P. H. (1963). Observations on the early development of smiling. In: B. M. Foss (Ed.), *Determinants of Infant Behavior II* (pp. 113-138). London: Methuen & Co. Ltd.
- [34] Breazeal, C. & Scassellati, B. (2000). Infant-like social interactions between a robot and a human caregiver. *Adaptive Behavior*, 8, 49-74.
- [35] Asada, M., MacDorman, K. F., Ishiguro, H., & Kuniyoshi, Y. (2000). Cognitive developmental robotics as a new paradigm for the design of humanoid robotics. In *Humanoids 2000: Proceedings of the First IEEE-RAS International Conference on Humanoid Robots*, September 7-8, MIT, Cambridge, MA.
- [36] Hollich, G. J. (1999). *Mechanisms of Word Learning: A Computational Model*. Unpublished Dissertation, Temple University, Philadelphia, PA.
- [37] Webb, B. (2001). Can robots make good models of biological behaviour? *Behavioral and Brain Sciences*, 24.
- [38] Williams, J. H. G., Whiten, A., Suddendorf, T., & Perrett, D. I. (in press). Imitation, mirror neurons and autism. *Neuroscience and Biobehavioral Reviews*.
- [39] Rodier, P. M. (2000). The early origins of autism. *Scientific American*, 282, 56-63.
- [40] Hickok, G., Bellugi, U. & Klima, E. S. (2001). Sign language in the brain. *Scientific American*, 284, 58-65.