D	E	S	C	5	6	5		Operator: Zheng Yuexia	Dispatch: 01.11.06	PE: Rita Matos
Journal Name				Manuscript No.				Proofreader: Zhang Yeping	No. of Pages: 8	Copy-editor:

Developmental Science 10:1 (2007), pp 61–68 DOI: 10.1111/j.1467-7687.2007.00565.x

The dynamic lift of developmental process

Linda B. Smith[1] and Cynthia Breazeal[2]

1. Department of Psychological and Brain Sciences, Indiana University, USA
2. Media Lab, Massachusetts Institute of Technology, USA

Abstract

What are the essential properties of human intelligence, currently unparalleled in its power relative to other biological forms and relative to artificial forms of intelligence? We suggest that answering this question depends critically on understanding developmental process. This paper considers three principles potentially essential to building human-like intelligence: the heterogeneity of the component processes, the embedding of development in a social world, and developmental processes that change the cognitive system as a function of the history of soft-assemblies of these heterogeneous processes in specific tasks. The paper uses examples from human development and from developmental robotics to show how these processes also may underlie biological intelligence and enable us to generate more advanced forms of artificial intelligence.

Introduction

There are fields of contemporary research that seem on the edge of science fiction. One of these is anthropomorphic robotics, founded with the goal of building physically intelligent devices that interact in the world in ways similar to people, that is, devices that think, plan, use language, have friends, play (see, e.g. Breazeal, 2003; Goetz, Keisler & Powers, 2003; Pfiefer & Scheier, 1999). This goal may seem a flight of fancy, but is it? The idea of a flying machine defined that status once but nonetheless engineers deciphered the principles of flying well enough to build machines that fly.

What are the key principles for engineering human-like intelligence? One subfield in robotics is placing its bets on developmental process (Zlatev & Balenius, 2001). Epigenetic robotics is based on that observation that the highest forms of biological intelligence have long periods of immaturity and on the assumption that this immaturity is mechanistically crucial to the ultimate power of that intelligence. Creating robots that develop human-like intelligence requires that we human developmentalists do our side of the job, by determining the relevant principles of developmental change.

What would such principles look like? To continue the flying machine analogy, not all the properties of birds are relevant to engineering planes; feathers, hollow bones, flapping wings, beaks, and egg-laying are not at all essential. Instead, the key principle is aerodynamic lift. We need comparable developmental principles that point to the essential and mechanistically realizable processes of cognitive growth. Although we are surely far from such an understanding, in celebration of this anniversary issue, we consider three principles, as revealed in human development and as applied in epigenetic robotics.

Principle 1: Coordination of sensory-motor activity

In his theory of the origins of intelligence, Piaget (1952) pointed to the in-task coordination of sensory-motor processes in physical tasks as the starting point for higher intelligence. Contemporary computational theorists (Lungarella, Pegors, Bullwinkle & Sporns, 2005; Lungarella & Sporns, 2005) agree. Simulations and mathematical analyses show how the coordination of heterogeneous processes (such hearing and seeing, or seeing and reaching) in the performance of a task drives self-organizing change. Others have speculated that a developmental history of such multiple coordinations yields higher-order generalizations that transcend those very sensory systems (see, e.g. Barsalou, Pecher, Zeelenberg, Simons & Hamann, 2005; Smith & Gasser, 2005).

In the literature on human development, there are many well-documented demonstrations of such coordinations as mechanisms of change (e.g. Gibson, 1969; Bushnell, 1994; Ruff & Rothbart, 1996; Amso & Johnson, in press). In one recent and remarkably inventive demonstration, Needham, Barrett and Peterman (2002) fit 2- to 5-month-old infants with Velcro-covered 'sticky mittens'. These mittens enabled the infants to grab objects merely

Address for correspondence: Linda B. Smith, Department of Psychological and Brain Sciences, Indiana University, 1101 East 10th Street, Bloomington, IN 47405, USA; e-mail: smith4@indiana.edu

by swiping at them, enabling them to more successfully coordinate vision and reaching than their limited motor skill would normally allow. Infants who were given 2 weeks of experiences with ‘sticky’ mittens subsequently showed more sophisticated object exploration even *with the mittens off*. They looked at objects more, made more visually coordinated swipes at objects, and produced more combined visual and *oral* exploration of objects than did control infants who had no exploratory experiences with ‘sticky mittens’. In brief, giving infants the ability to coordinate seeing and reaching in the task of physically contacting objects promoted change in processes of visual attention.

Such coordinations may also enable the discovery of deeper regularities. One demonstration of this point concerns visual object recognition and the definition of an object’s axes of elongation and symmetry, structural aspects of three-dimensional object shape that play an important role in recognizing objects from multiple perspectives and also in categorization (e.g. Marr, 1982). In a recent study, Smith (2005) showed that for young children ($2\frac{1}{2}$-year-olds), action played a significant role in the definition of these structural dimensions.

In one experiment in this series, children held and moved an object like that shown in Figure 1, an object that did not have a single main axis of elongation. In one condition, children moved the object up and down along a 1-meter vertical path. In a second condition, they moved the object back and forth on a 1-meter horizontal path. Immediately following, children were asked to group the exemplar object with other like things. No movement was involved in this categorization task. Children who had acted on the exemplar by moving it vertically grouped it with objects elongated on their vertical axes (Figure 1B), but children who had moved the exemplar horizontally grouped it with objects elongated on their horizontal axes. These categorization choices emerged only as a consequence of action and not when children merely observed someone else move the exemplar along the same path. The path of action apparently selected or highlighted the corresponding axis, altering the perceived similarity of the exemplar to the test objects.

A second experiment used an exemplar like that shown in Figure 1C, an exemplar not quite symmetrical around its center axis. The actions are illustrated in Figure 1D. Children who held the exemplar in one hand by one part and moved it back and forth subsequently grouped the exemplar with objects that were less symmetrical in shape than the exemplar itself, as if they saw the exemplar as composed of two unequal parts. Children who held the exemplar in the two hands and rotated it about a central axis subsequently grouped the exemplar with objects more symmetrical in shape than the exemplar,

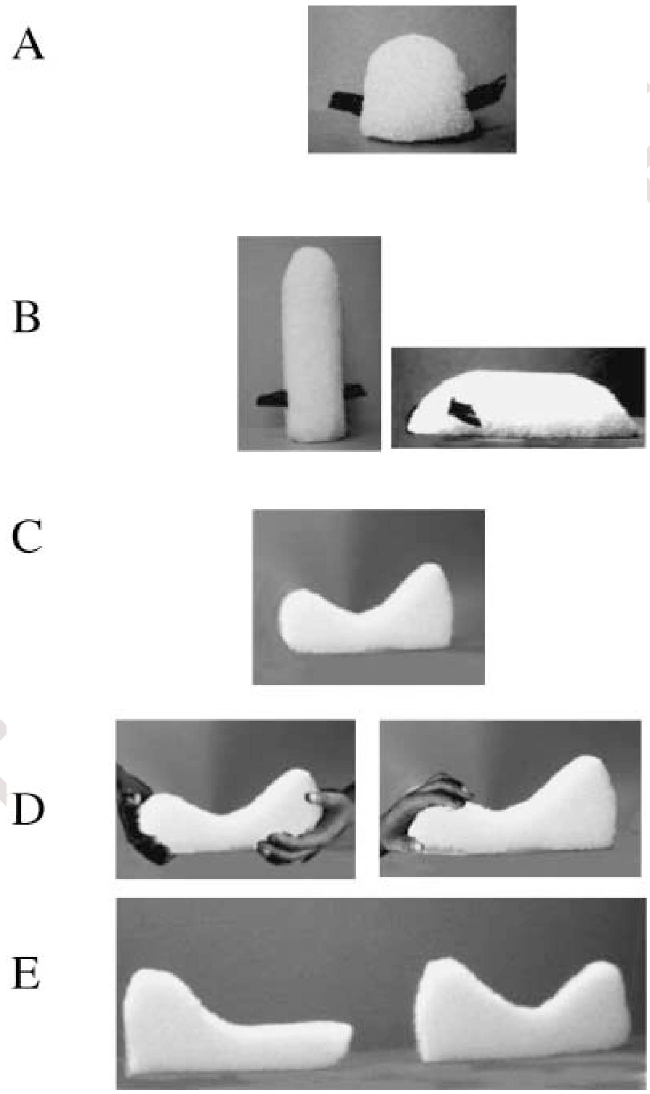

Figure 1 *An exemplar (A), sample choice objects for the axes-of-elongation categorization task, the exemplar (C), the two actions (D) and sample choice objects for the axes-of-symmetry categorization task.*

as they saw the exemplar as composed of two comparable and symmetric parts. Again, these results only obtained when children acted on the objects, not when they watched someone else do the action. The enacted action appears to have selected *compatible* visual descriptions of object shape.

Axes of elongation and symmetry are higher-order dimensions of object shape fundamental to processes of human object recognition (Marr, 1982), yet they may be developmentally defined not by vision alone but by the in-task coordination of visual and motor processes. The finding that action influences visual perception fits a long literature on perceptual development (e.g. Gibson, 1969;

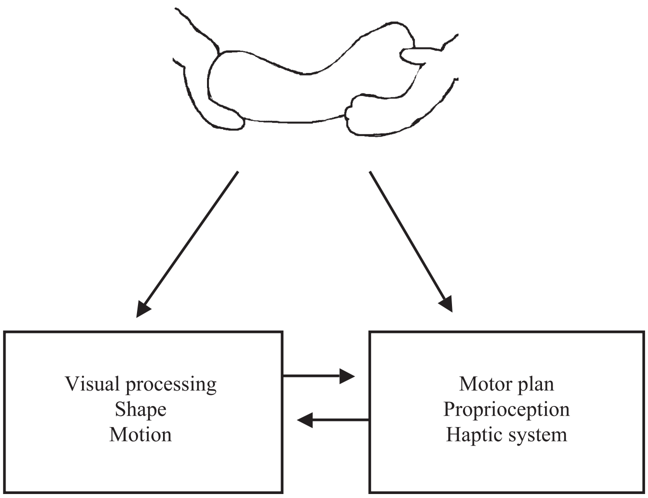

Figure 2 *The coordination of vision and action.*

Held & Hein, 1963) as well as newer research on adult cognition showing multi-modal interactions and priming effects in object recognition (e.g. Barsalou *et al*., 2005; Ellis & Tucker, 2000).

The idea that the in-task coordination of heterogeneous systems creates change in those systems has been proposed as a fundamental mechanism of neural development by Edelman (1987). Figure 2 illustrates the proposed process through five kinds of inter-related mappings that emerge as an infant holds, moves and explores objects. One map is between the physical properties of the object and the neuronal activity in the visual system. Other maps are between the physical properties of the object and neuronal activity in the haptic, proprioceptive and motor-planning systems. A third kind of map is between these systems and the sensory input; as the hands move, the object moves, presenting new sensory information to all the components. Finally, there are what Edelman calls the re-entrant maps: activity in the visual system is mapped to the haptic, motor-planning, and proprioceptive systems, and activity in these systems is mapped to the visual system. Thus the independent mappings of the stimulus – the sight and the manual feel – provide qualitatively different glosses on the world. But each of those different glosses is about the same reality and each serves as an input to other components in the system. By providing different information but by being coupled, these heterogeneous processes create a self-organizing system that may be able to find structure in the input that is not available in any one component process.

Sensori-motor coordinations also provide developmental lift for anthropomorphic robots. As one example, we consider how one robot learned a map between its own body and that of a human being (Breazeal, Buchsbaum, Gray, Gatenby & Blumberg, 2005). The implementation begins with the following systems in place in the robot: (1) the ability to visually track the facial features of a person, (2) the ability to 'motor babble' by exercising an initial repertoire of facial movements, (3) the ability to sense its own facial configuration, (4) a coarse mapping of 'organ relations' that roughly relate regions of the robot's own face to regions of the perceived face of others *but without any specification for how movement* of these regions correspond to one what one sees or feels, and (5) a contingency metric that determines whether a visually seen movement is temporally contingent on the robot's own movement.

The task that couples these systems and thus creates developmental change derives from studies of human development, and particularly the finding that *adults* often imitate the facial expressions of infants (e.g. Jones, 2006). As the robot 'motor babbles' by exercising its repertoire of facial expressions, the human participant imitates the robot as shown in Figure 3. Although the robot cannot see its own face, it can sense its facial configuration via proprioception. As the robot moves its face from expression to expression, it visually observes how the human's face responds.

Through these processes, the robot attentively selects pairings of matched regions between its own face to that of the person. These pairings *teach* the system the transformation from the visual movements of the human's face to the robot's own corresponding motor movements, building an intermodal representation that relates the sight of another's actions to the motor plans for one's own actions and does so through a unified *motor-based coordinate system*. In brief, the robot has acquired a 'mirror system' *that can be used in other tasks*. This development – like the definition of axes of elongation and symmetry – is emergent in the real-time coordination of perceiving and acting. The achievement of a mirror system is also dependent on perceiving and acting in a world with other similarly structured intelligent agents.

Principle 2: Coupled to intelligent others

The highest forms of biological intelligence reside in a social world; development takes place among conspecifics with *similar internal systems and similar external bodies*. The importance of the social embeddedness of human cognition is well recognized in the literature (e.g. Striano & Stuart, 2005; Markova & Legerstee, 2006; beyond infancy see Rogoff, 2003). Perhaps less well recognized (but see, Yu & Smith, 2006; see also Smith, 2000a, 2000b and Yu, Ballard & Aslin, 2005) is how this social embeddedness is itself made manifest in the sensory-motor coordinations we refer to under Principle 1.

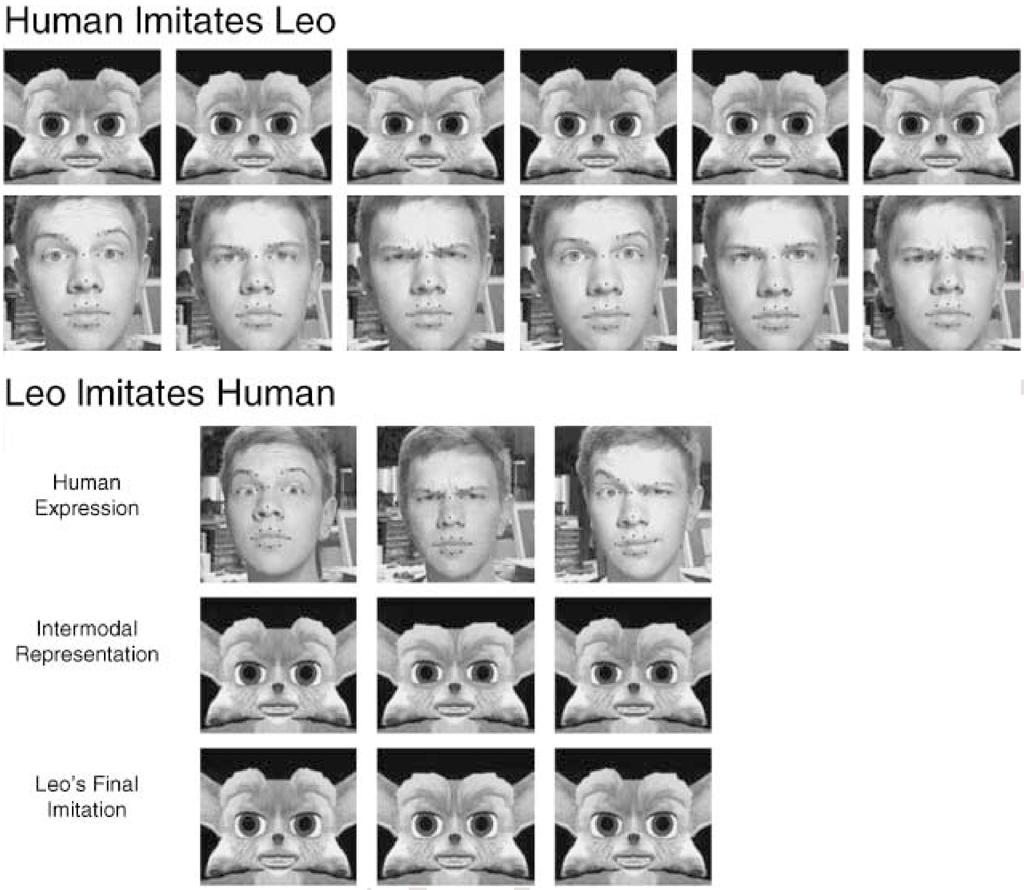

Figure 3 *Top: As the robot spontaneously generates facial gestures, a human imitates those facial gestures. Bottom: After such training the robot can imitate new facial gestures.*

Figure 4 illustrates the couplings between one's own internal states, one's outward bodily behaviors, the bodily behaviors of others, and their internal states. Crucially, the body and its behaviors are observable by others. But because observable behaviors are also linked to (indeed, are driven by) the actor's internal state, observable bodily behaviors also provide (albeit imperfect) information to others about those internal states. Because one's bodily actions also influence the internal states of others, one's own actions are also (albeit indirectly) linked to the internal states of others. In brief, development occurs within a complex system of coupled behaviors, coupled bodies, and coupled cognitive systems. These couplings generate a network of learnable correlations: between the appearance of the self and the appearance of others, between the behavior of the self and the behavior of others, between one's own bodily behaviors and one's internal states, between the external states of others and one own's internal states. In ways deeply analogous to the interactions of vision and action in the definition of an object's structural shape or in the origins of a mirror system, these correlations can yield transcendent higher-order regularities, in this case, about intentions and motivations (see Smith, 2000b). The dynamic socially embedded coupling of two intelligent systems – to each other through similar bodies and behaviors – is a potent agent of change and, indeed, may be sufficient for a perceiving and acting machine, a robot, to develop socially adept responses that reflect beliefs about the internal states of others.

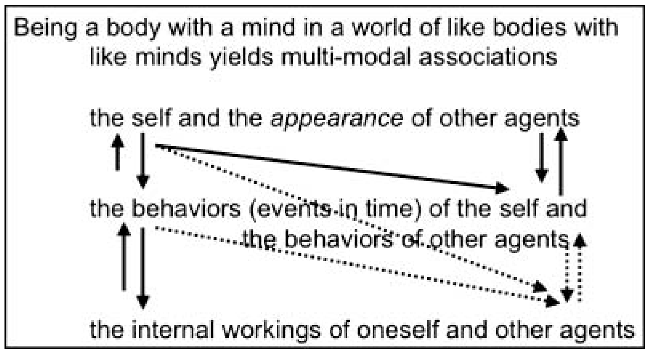

Figure 4 *Higher-order correlations available to the self from the coupling of behavior.*

Breazeal's group (Gray, Breazeal, Berlin, Brooks & Lieberman, 2005) has implemented this idea in a robot who understands others by attempting to simulate – in its own cognitive system – the behaviors of others. The implementation is based on experiments with human adults showing a dual affect–body connection whereby posing one's face into a specific emotive expression actually *elicits* the feeling associated with that emotion (Strack, Martin & Stepper, 1988, Niedenthal, Barsalou, Winkielman, Krauth-Gruber & Ric, 2005). Hence, imitating the facial expressions of others is a mechanism that could internally generate the *feelings* of another. Doing this would enable the developing robot (or infant) to learn what the other is feeling, thereby allowing the robot (or infant) to learn the association of observed emotive expressions with the robot's (or infant's) own internal affective states. In this way, robots (and infants) could leverage their earlier acquired mirror system to decode emotional messages conveyed through facial expressions.

The robotic implementation (see Thomaz, Berlin & Breazeal, 2005; Breazeal, 2003) uses a simple appraisal process based on Damasio's theory of somatic markers (1994). Specifically, incoming perceptual and internal states are tagged with affective information, valence (positive or negative), arousal (high or low), and novelty. Further, based on Fernald's (1989) work with human infants, the robot comes equipped with hardwired affective appraisals of simple acoustic features of human speech (pitch, energy variance; see Breazeal & Aryananda, 2002).

The task that couples these processes and in so doing drives developmental change is once again, face-to-face interaction. Because of the dual body–affect pathways, when the robot reproduces the emotive facial expressions of others, it evokes the corresponding affective state (in terms of arousal and valence variables). This is reinforced by affective information coming from the person's speech signal. These time-locked inter-actor multi-modal states occur because of the similarity in bodies and body–affect mappings, and they enable the robot to associate its internal affective state with the corresponding observed expression, and thus, the internal state of the social partner. The principle behind this developmental achievement is, again, coordination of heterogeneous sensory and motor systems in a specific task; but now there is also the coupling of these activities (and the internal states that give rise to them) to those of an externally and internally similar social partner.

Principle 3: Overlapping coordinations

Developing organisms do not solve just one task; they solve many overlapping tasks all drawing on many component processes (Thelen & Smith, 1994). Further, biologically developing systems typically confront these tasks in a particular sequence. Research on the development of biological intelligence strongly suggests that this is a key ingredient of developmental process: overlapping component processes engaged in the solution of many inter-related and ordered tasks. One area in which this is seen is in the natural ordering of the development of sensory-motor systems, and in the cascading developmental consequences of altering that natural order. In non-human species, experiments have been conducted that re-order the development of the systems in non-human species (e.g. reversing the natural order in which audition and vision come online). The outcome is dramatically altered neural and behavioral development (see, Knudsen, 2003; Turkewitz & Kenny, 1985; Lickliter, 1993; Rosenblatt, Turkewitz & Schneirla, 1969). Analogous effects are found in children with significant sensory deficits. For example, in typically developing children, hearing and the coordination of hearing and vision appear to play an organizing role in the development of visual attention. In deaf children, vision attention develops without audition; experimental and observational results suggest that the consequence is altered processes of visual attention, including greater sensitivity to motion and as a consequence may be both more sensitive to some kinds of information (e.g. Armstrong, Hillyard, Neville & Mitchell, 2002) and also more distractible (see Mitchell & Quittner, 1996; Smith, Quittner, Osberger & Miyamoto, 1998; Horn, Davis, Pisoni & Miyamoto, 2005). Development builds on itself through the self-organizing consequences of the interactions of many components, each of those interactions changes the components, potentially the system as a whole, and in so doing constrains possible future development.

A good example of this general principle is the well-documented effects of self-locomotion on infants' performances in Piaget's (1952) A-not-B task. In this task an object is repeatedly hidden at one location (A) and then on a critical switch trial is hidden at a new location (B). On this B trial, infants younger than 12 months typically reach, not to where they saw the object disappear, but back to A. Piaget understood this task in terms of infants' ability to mentally represent objects independent of their own actions. In his account, infants reached back to A because their representations (or memories) for the object were tightly tied to the sensory-motor processes through which they acted on those objects. In a landmark study, Bertenthal, Campos and Barrett (1984; see also Bertenthal & Campos, 1990) noted that the developmental timing of infant success in Piaget's task; that by 12 months of age, infants no longer perseverate on the critical B trial corresponded to an age at which infants have had several months of experience

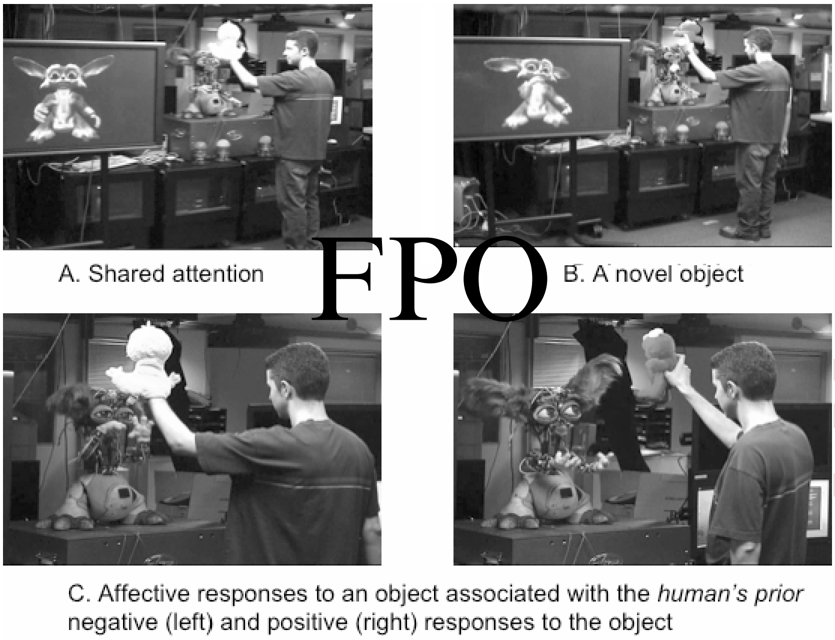

Figure 5 *Three behaviors important to social referencing: (A) shared attention with a human, (B) apprehension and interest to a novel object, and (C) emotional responses to objects that have been associated with affective appraisals offered by the human.*

crawling and are beginning to walk. In an analysis of individual patterns of development, they found strong correlations between experience in self-locomotion and non-perseverative (that is, correct) responding in the A-not-B task. They also experimentally tested their idea that self-locomotion was the driver of developmental change by putting babies in walkers, giving them early experience in self-locomotion. This experience accelerated the development in the A-not-B task, leading to months earlier flexible (nonperseverative) responding. Why should experience in moving oneself about the world help one better remember the most recent location of an object? Because success in the A not B task depends on many component processes (see Smith, Thelen, Titzer & McLin, 1999) including spatial discrimination and the successive ordering of different actions that are also involved in self-locomotion.

We conclude with a final example from epigenetic robotics, a demonstation of how the emergence of social referencing (in the robot) may arise out of overlapping achievements that emerge from the coordination of sensory-motor processes in socially shared tasks (see Breazeal & Arynanda, 2002: Breazeal *et al*., 2005; Thomaz *et al*., 2005). Social referencing refers to an infant's (or robot's) ability to use the affective appraisal of another to guide its own reaction to a novel object. One component ability in this achievement is the assessment of another's affective state. Human infants discriminate the facial expressions of others by responding with smiles and frowns of their own (e.g. Trevarthen, 1979; Neslon, Parker & Guthrie, 2006), a process that may work in part through emotion contagion (Feinman, 1982; Jones & Hong, 2001; Jones & Raag, 1989). This is implemented in the robot through the emotional empathy system described earlier. A second component is the linking of these appraisals to the object (Feinman, 1982; Jones, Raag & Collins, 1990). With respect to the robot, these are implemented in a memory system that enables the robot to tag object representations with somatic markers using an associative learning mechanism (Thomaz *et al*., 2005). For social referencing to work, however, the object linked to the affective appraisal must be the one to which the social partner is attending. Thus, the third component is the ability to determine the referent of the social partner's attention, which is achieved in infants (e.g. Butterwoth 1991) and in the robot through gaze following.

More specifically, the robot's attentional system computes the level of saliency for objects and events by integrating three sources of information: (1) the perceptual properties in the field (the proximity of objects to the robot, contrast, movement), (2) the internal state of the robot (recent past events, goals); and (3) the bodily signals of the social partner (e.g. direction of eye gaze, or points). The overall saliency at each time step is the weighted sum of these factors (Breazeal & Scassellati, 1999). In this analysis, then, joint attention does not replace or over-ride other attentional processes but works through them (see also, Yu *et al*., 2005; Samuelson & Smith, 1998; Smith, 2000b).

Figure 5 illustrates overlapping competencies that emerge from these processes and that culminate in social referencing. When the robot is confronted by a novel object, the object appraisal mechanism tags the object with novelty, which biases the emotion system to evoke a state of mild anxiety. This results in an increased tendency to look to the human's face to 'soothe' itself. At this point, naïve human participants react in ways that seem entirely natural and also highly effective for robot development. For example, when the human notices the robot's initial wariness to the unknown object, the human participant often attempts to engage the robot and familiarize it with the toy. The robot's attention system determines the robot's focus of attention, monitors the attentional focus of the human, and uses both to keep track of the referential focus. The fact that the human is gazing and reacting toward the novel toy draws the robot's attentional focus to it as well. The robot's initial looks to the human's face (triggered by the 'anxious' response) allow the robot to witness the partner's emotional response. The empathic mechanism described previously enables the robot to extract the affective meaning from the human's facial expression, and the affect is bound to the object.

In this robotic system, neither social referencing nor joint attention are isolated or modularized skills in the robot. Instead, they emerge incrementally through the integration of past achievements, achievements that themselves are consequences of the agent's sensory-motor interactions in a physical and social world. This robot's developmental achievements illustrate what may be a profound truth about developmental process, and why evolution selected development as the mechanism through which to make intelligence. Overlapping coordinations, multiple integrations of many component processes in a variety of inter-related tasks, yield the self-organizing emergence of increasingly complex cognitive functions. It is the multiple integrations of many component processes in many different tasks that leads to a system that is flexible, inventive, and exquisitely adaptive.

Why development?

The intellectual achievements of humankind are daunting, as is the task of scientists trying to explain how they come about. Evolution selected development as the process through which to achieve this intelligence; accordingly, it may only be through development that we will understand that intelligence or hope to emulate it in machines. Certainly, the idea of engineering human-like intelligence seems both impertinent and at least a bit ahead of itself. But there are lessons to be learned from the trying. Recent advances in the study of human development and in the application of these ideas in the field of epigenetic robotics suggest the core developmental principles: the coordination of distinct sensory-motor processes, the coupling of like cognitive systems through like bodies in shared tasks, and a history of multiple and overlapping integrations. This is the dynamic lift of developmental process.

References

Amso, D., & Johnson, S.P. (in press). Learning by selection: visual search and object perception in young infants. *Developmental Psychology*.

Armstrong, B., Hillyard, S.A., Neville, H.J., & Mitchell, T.V. (2002). Auditory deprivation affects processing of motion, but not color. *Cognitive Brain Research*, **14**, 422–434.

Barsalou, L.W., Pecher, D., Zeelenberg, R., Simmons, W.K., & Hamann, S.B. (2005). Multimodal simulation in conceptual processing. In W. Ahn, R.L. Goldstone, B.C. Love, A. Markman, & P. Wolff (Eds.), *Categorization inside and outside the lab: Festschrift in honor of Douglas L. Medin* (pp. 249–270). Washington, DC: American Psychological Association.

Bertenthal, B.I., & Campos, J.J. (1990). A systems approach to the organizing effects of self-produced locomotion during infancy. In C. Rovee-Collier & L.P. Lipsitt (Eds.), *Advances in infancy research* (vol. 6, pp. 1–60). Norwood, NJ: Ablex.

Bertenthal, B., Campos, J., & Barrett, K. (1984). Self-produced motion: an organizer of emotional, cognitive, and social development in infancy. In R. Emde & R. Harmon (Eds.), *Continuities and discontinuities* (pp. 175–210). New York: Plenum Press.

Breazeal, C. (2003). Emotion and sociable humanoid robots. In E. Hudlika (Ed.), *International Journal of Human Computer Interaction*, **59**, 119–155.

Breazeal C., & Aryananda, L. (2002). Recognizing affective intent in robot directed speech. *Autonomous Robots*, **12** (1), 85–104.

Breazeal, C., Buchsbaum, D., Gray, J., Gatenby, D., & Blumberg, B. (2005). Learning from and about others: towards using imitation to bootstrap the social understanding of others by robots. L. Rocha and F. Almedia e Costa (Eds.), *Artificial Life*, **11** (1–2), 1–32.

Breazeal, C., & Scassellati, B. (1999). A context-dependent attention system for a social robot. *Proceedings of the Sixteenth International Joint Conference on Artificial Intelligence (IJCAI 99)* (pp. 1146–1151). Stockholm, Sweden.

Bushnell, E. (1994). A dual processing approach to cross-modal matching: implications for development. In D. Lewkowicz & R. Lickliter (Eds.), *The development of intersensory perception* (pp. 19–38). Mahwah, NJ: LEA.

Butterworth, G. (1991). The ontogeny and phylogeny of joint visual attention. In A. Whiten (Ed.), *Natural theories of mind* (pp. 223–232). Oxford: Blackwell.

Damasio, A. (1994). *Descartes' error: Emotion, reason, and the human brain*. New York: G.P. Putnam and Sons.

Edelman, G. (1987). *Neural Darwinism*. New York: Basic Books.

Ellis, R., & Tucker, M. (2000). Micro-affordance: the potentiation

of components of action by seen objects. *British Journal of Psychology*, **91** (4), 451–471.
Feinman, S. (1982). Social referencing in infancy. *Merrill-Palmer Quarterly*, **28**, 445–470.
Fernald, A. (1989). Intonation and communicative intent in mother's speech to infants. *Child Development*, **60**, 1497–1510.
Gallese, V., & Goldman, A. (1998). Mirror neurons and the simulation theory of mind-reading. *Trends in Cognitive Sciences*, **2** (12), 493–501.
Gray, J., Breazeal, C., Berlin, M., Brooks, A., & Lieberman, J. (2005). Action parsing and goal inference using self as simulator. *Proceedings of Fourteenth IEEE Workshop on Robot and Human Interactive Communication (Ro-Man05)*, Nashville, TN.
Horn, D., Davis, R., Pisoni, D., & Myamoto, R. (2005). Development of visual attention skills in prelingually deaf children who use cochlear implants. *Ear and Hearing*, **26**, 389–408.
Jones, S. (2006). Infants learn to imitate by being imitated. Proceedings of the 5th International Conference of Development and Learning.
Knudsen, E. (2003). Instructed learning in the auditory localization pathway of the barn owl. *Nature*, **417** (6886), 322–328.
Lickliter, E. (1993). Timing and the development of perinatal perceptual organization. In G. Turkewitz & D. Devenney (Eds.), *Developmental time and timing* (pp. 105–123). Hillsdale, NJ: LEA.
Lungarella, M., Pegors, T., Bulwinkle, D., & Sporns, O. (2005). Methods for quantifying the informational structure of sensory and motor data. *Neuroinformatics*, **3**, 243–262.
Lungarella, M., & Sporns, O. (2005). Information self-structuring: key principle for learning and development. *Proceedings 2005 IEEE International Conference on Development and Learning* (pp. 25–30).
Mitchell, T.V., & Quittner, A.L. (1996). Multimethod study of attention and behavior problems in hearing-impaired children. *Journal of Clinical Child Psychology*, **25** (1), 83–96.
Needham, A., Barrett, T., & Peterman, K. (2002). A pick me up for infants' exploratory skills: early simulated experiences reaching for objects using 'sticky' mittens enhances young infants' object exploration skills. *Infant Behavior and Development*, **25** (3), 279–295.
Niedenthal, P.M., Barsalou, L.W., Winkielman, P., Krauth-Gruber, S., & Ric, F. (2005). Embodiment in attitudes, social perception, and emotion. *Personality and Social Psychology Review*, **9** (3), 184–211.
Piaget, J. (1952). *The origins of intelligence in children*. Oxford: International Universities Press.
Plutchik, R. (1991). *The emotions*. Lanham, MD: University Press of America.
Rogoff, B. (2003). *The cultural nature of human development*. New York: Oxford University Press.
Rosenblatt, J.H.R., Turkewitz, G., & Schneirla, T.C. (1969). Development of home orientation in newborn kittens. *Transactions of the New York Academy of Sciences*, **31**, 231–250.
Ruff, H.A., & Rothbart, M.K. (1996). *Attention in early development: Themes and variations*. New York: Oxford University Press.
Samuelson, L.K., & Smith, L.B. (1998). Memory and attention make smart word learning: an alternative account of Akhtar, Carpenter, and Tomasello. *Child Development*, **69**, 94–104.
Smith, L.B. (2000a). How to learn words: an associative crane. In R. Golinkoff & K. Hirsh-Pasek. (Eds.), *Breaking the word learning barrier* (pp. 51–80). Oxford: Oxford University Press.
Smith, L.B. (2000b). Avoiding association when its behaviorism you really hate. In R. Golinkoff & K. Hirsh-Pasek. (Eds.), *Breaking the word learning barrier* (pp. 169–174). Oxford: Oxford University Press.
Smith, L.B. (2005). Action alters shape categories. *Cognitive Science*, **29** (4), 665–679.
Smith, L.B., Quittner, A.L., Osberger, M.J., & Miyamoto, R. (1998). Audition and visual attention: the developmental trajectory in deaf and hearing populations. *Developmental Psychology*, **34** (5), 840–850.
Smith, L.B., Thelen, E., Titzer, R., & McLin, D. (1999). Knowing in the context of acting: the task dynamics of the A-not-B error. *Psychological Review*, **106** (2), 235–260.
Strack, F., Martin, L., & Stepper, S. (1988). Inhibiting and facilitating conditions of the human smile: a nonobtrusive test of the facial feedback hypothesis. *Journal of Personality and Social Psychology*, **54**, 768–777.
Striano, T., & Bertin, E. (2005). Social-cognitive skills between 5 and 10 months of age. *British Journal of Developmental Psychology*, **23** (4), 559–568.
Thomaz, A.L., Berlin, M., & Breazeal, C. (2005). An embodied computational model of social referencing. *Proceedings of Fourteenth IEEE Workshop on Robot and Human Interactive Communication (Ro-Man05)*, Nashville, TN.
Trevarthen, C. (1979). Communication and cooperation in early infancy: a description of primary intersubjectivity. In M. Bullowa (Ed.), *Before speech: The beginning of interpersonal communication* (pp. 321–348). Cambridge: Cambridge University Press.
Turkewitz, G., & Kenny, P.A. (1985). The role of developmental limitations of sensory input on sensory/perceptual organization. *Journal of Developmental and Behavioral Pediatrics*, **6**, 302–306.
Yu, C., Ballard, D.H., & Aslin, R.N. (2005). The role of embodied intention in early lexical acquisition. *Cognitive Science*, **29** (6), 961–1005.
Zlatev, J., & Balkenius, C. (2001). Introduction: Why epigenetic robotics? In C. Balkenius, J. Zlatev, H. Kozima, K. Dautenhahn, & C. Breazeal (Eds.), *Proceedings of the First International Workshop on Epigenetic Robotics: Modeling Cognitive Development in Robotic Systems* (pp. 1–4). Lund University Cognitive Studies, 85.

Author Query Form

Journal: Developmental Science

Article: desc_565.fm

Dear Author,

During the copy-editing of your paper, the following queries arose. Please respond to these by marking up your proofs with the necessary changes/additions. Please write your answers on the query sheet if there is insufficient space on the page proofs. Please write clearly and follow the conventions shown on the attached corrections sheet. If returning the proof by fax do not write too close to the paper's edge. Please remember that illegible mark-ups may delay publication.

Many thanks for your assistance.

No.	Query	Remarks
1	Please supply higher resolution Fig. 5. For more information about supplying electronic artwork, please see our the journal webpage or our electronic artwork guidelines at http://www.blackwellpublishing.com/authors/digill.asp	

MARKED PROOF

Please correct and return this set

Please use the proof correction marks shown below for all alterations and corrections. If you wish to return your proof by fax you should ensure that all amendments are written clearly in dark ink and are made well within the page margins.

Instruction to printer	*Textual mark*	*Marginal mark*
Leave unchanged	• • • under matter to remain	Ⓥ
Insert in text the matter indicated in the margin	⋏	New matter followed by ⋏ or ⋏Ⓧ2
Delete	/ through single character, rule or underline or ⊢⊣ through all characters to be deleted	ɗ or ɗⓍ2
Substitute character or substitute part of one or more word(s)	/ through letter or ⊢⊣ through characters	new character / or new characters /
Change to italics	— under matter to be changed	⌐
Change to capitals	≡ under matter to be changed	≡
Change to small capitals	= under matter to be changed	=
Change to bold type	~ under matter to be changed	~
Change to bold italic	≂ under matter to be changed	≂
Change to lower case	Encircle matter to be changed	≢
Change italic to upright type	(As above)	⊥
Change bold to non-bold type	(As above)	⊥
Insert 'superior' character	/ through character or ⋏ where required	Y or ⋏ under character e.g. Y or ⋏
Insert 'inferior' character	(As above)	⋏ over character e.g. ⋏
Insert full stop	(As above)	⊙
Insert comma	(As above)	,
Insert single quotation marks	(As above)	Y or ⋏ and/or Y or ⋏
Insert double quotation marks	(As above)	Y or ⋏ and/or Y or ⋏
Insert hyphen	(As above)	⊢⊣
Start new paragraph	⌐	⌐
No new paragraph	⌒	⌒
Transpose	⊔⊓	⊔⊓
Close up	linking ⁀ characters	⁀
Insert or substitute space between characters or words	/ through character or ⋏ where required	Y
Reduce space between characters or words	| between characters or words affected	⊤