Johansson, B., Şahin, E. & Balkenius, C. (2010). Proceedings of the Tenth International Conference on Epigenetic Robotics: Modeling Cognitive Development in Robotic Systems. Lund University Cognitive Studies, 149.

Infant Development Sequences for Shaping Sensorimotor Learning in Humanoid Robots

James Law **Mark Lee** **Martin Hülse**
Department of Computer Science
Aberystwyth University
Aberystwyth, Ceredigion, UK

Abstract

Early infancy is a time of remarkable learning and cognitive growth. Developmental psychologists have observed that very distinct stages in behaviour are related to such growth spurts. This paper presents the findings of a detailed review of the first 12 months of infant sensory and motor development, with the aim of providing an explicit framework that can guide the design of similar developmental processes in robotics. We show how human sensor and motor development sequences can be mapped on to robotic platforms and how constraints on perception and action can be applied or released in organized sequences so that staged behaviour and learning may take place. This approach, of using constraints as a scaffold, can effectively manage the complexity of learning a set of increasing sensorimotor skills, as in the human infant. We give examples of constraint structures that we are applying to an iCub humanoid robot.

1. Introduction

For robots to become truly autonomous they must be capable of continuously developing within their environment, to be motivated to explore and learn new abilities, and to adapt and build upon these abilities. Even for robots with limited sensing and actuating capabilities the complexity arising from interactions with the real world makes unconstrained learning unreliable and computationally demanding. Humans, by comparison, display remarkable talents in these areas, and are unfazed by issues that would disrupt a robot. Such abilities in humans are established in infancy through a cycle of staged development, which imposes a series of constraints that restrain the infant's action repertoire and sensing capabilities. Initially, these constraints reduce the perceived complexity of the environment and limit interaction, providing a scaffold that helps the infant to make sense of the world (Bruner, 1990, Rutkowska, 1994). These constraints are then gradually eased or lifted, allowing the infant to advance into a new stage of development (Rutkowska, 1994).

In our current research we are using these ideas of staged development to build a robotic learning architecture in which sensorimotor competence grows cumulatively. Our developmental framework, LCAS (Lift-Constraint, Act, Saturate), involves an overarching constraint framework that restricts the ranges and number of parameters available to the robot, but which are gradually released in a way that scaffolds learning (Lee et al., 2007a). Initially the robot is restricted to minimal sensor and motor facilities, providing it with a simplified relationship with its environment, and it begins to learn the relationships between these limited systems. At some point learning saturates and a constraint is eased or lifted, giving the robot access to more capabilities, and the cycle repeats. As an example, if the vision channel is markedly constricted then visual input will not interfere with, say, arm movement; thus the learning of arm action and its correlation with key proprioceptive feedback may proceed without any confusing visual contingencies.

To create this programme of constraints, we look to the developmental stages in infancy for inspiration. We begin this paper by reviewing the considerable literature from developmental psychology and highlight the observable stages in infant sensorimotor development. From this data we derive a set of constraints to implement on our robots that are likely to produce similar developmental stages. Some constraints will be programmed to occur in an emergent way, while others will occur naturally.

Even in robots that are functionally, but not structurally, similar to an infant, the development sequence can provide inspiration for staged learning. For example, in our work we are focusing on development of sensorimotor skills in an iCub robot (Metta et al., 2008). We consider the vision, proprioception, vestibular and joint system to be sufficiently functionally similar to that of an infant for our investigations.

The work in this paper can be seen as an approach to robot shaping. Shaping refers to "a developmental approach, where the subject is allowed to refine its skills a[s] it masters the different tasks in the sequence as they become progressively harder" (Erez and Smart, 2008). Shaping is a mechanism of structuring the learning of a specific skill, e.g. reaching (Schlesinger et al., 2000), by creating a sequence of subtasks that progressively promote learning toward the desired skill. These subtasks and sequences are engineered with the final goal in mind. Our work is also inspired by the field of developmental robotics (Lungarella et al., 2003, Asada et al., 2009, Stoytchev, 2009) where robot learning and development strategies are inspired by the learning processes observed in young children and infants. We combine these approaches, using the stages in child development to inspire a shaping process. In the proposed framework skills such as visual attention and reaching, are built by following the constraints sequences in infancy which restrict accuracy and onset of joint control, and sensitivity and resolution of visual systems. With constraints released in an emergent manner, dependant on the developmental trajectory, such an approach removes the need for engineering learning sequences, and will provide more flexible and adaptive learning.

In the following sections we review observations from the developmental psychology literature on the first 12 months of human infant development, show how this information can be converted into a time line for robotic development, and give examples of constraints systems for learning several fundamental skills that are derived from it.

2. The first 12 months

Although a great deal of development occurs in the prenatal stages, it is not entirely clear whether, or how, very early foetal behaviours impact on the development of postnatal skills. For this reason, we base our work on the well documented development of abilities in the months after birth. A summary of that literature follows.

2.1 Birth

At birth an infant has relatively poor muscle control and tone, and tends to adopt a foetal posture (Shirley, 1933, Sheridan, 1973). When lifted, or pulled to sitting, limb and neck muscles demonstrate only enough tone to hold for a few seconds before relaxing (Sheridan, 1973). Eye muscles are the most active, possibly due to the high power to weight ratio.

The senses are all partially developed at birth (Butterworth and Harris, 1994). The neonate recognises sounds, and can identify its mothers voice (De Casper and Fifer, 1980) and the direction of a sound source (Muir and Field, 1979). It freezes in response to quiet, continuous sounds, but will blink or open its eyes wide in response to sudden noise (Sheridan, 1973). The neonate has taste preferences (Steiner, 1979); recognises smells, including its mothers (by 6 days) (MacFarlane, 1975); and responds to tactile stimulus. Vision is the most underdeveloped sense, although it is deemed sufficient for an infant's needs (Butterworth and Harris, 1994).

The neonate has coarse colour perception (Adams et al., 1994), but sees a diffuse image with a lack of clarity in the centre of the visual field (Oates et al., 2005). It prefers simple visual stimuli, curves, moving stimuli, 3D stimuli, and faces (Fantz, 1963), especially that of its mother (Field et al., 1984, Bushnell, 2001). As it ages, the infant will begin to prefer more complex shapes. It will turn its eyes to look at diffuse lights, but shows aversion to sudden bright light by closing its eyes (Sheridan, 1973). The resolution of the neonates vision, and its sensitivity to stimulus, are initially low, but improve over the first 6 months (Hainline, 1998).

Many reflexes are active at birth including the stepping reflex, startle reflex (Illingworth, 1983), rooting reflex, and tonic neck reflex (Butterworth and Harris, 1994).

2.2 Birth-1 month

Infant development progresses rapidly in the first post-natal month. Muscle tone improves, and neck tone becomes sufficient for the infant to lift its head for a few seconds at a time (Shirley, 1933, Griffiths, 1954, Sheridan, 1973, Fiorentino, 1981). With the increase in muscle tone the infant begins to turn both its head and eyes toward light and sound sources (Sheridan, 1973).

The infant can initially only focus at a distance of around 21cm, and nonconjugate vision is common (Fiorentino, 1981). Interestingly, this focal distance relates to the distance to the mother's face when held (Butterworth and Harris, 1994). Eye saccades are few in number, and fixate on object edges, rather than internal features(Maurer and Maurer, 1988). The infant stares at diffuse lights and colours, and is attracted to moving objects within its focal range (Sheridan, 1973).

Large, jerky movements begin to occur in the arms and, to a lesser extent, the legs (Sheridan, 1973). Although the hands are mainly fisted, fingers fan out when the arms are extended (Sheridan, 1973), a similar effect is also noticed in the feet and toes.

2.3 1-2 months

The infant has enough muscle tone to lift and support its head when prone (Griffiths, 1954) and to begin to lift its chest (Shirley, 1933).

Focal ability continues to improve, with acuity undergoing greatest improvement over the next month (Oates et al., 2005), although colour discrimination is already similar to that of an adult (Kellman and Arterberry, 1998). The field of view also increases from around 20 degrees at 6 weeks to 40 degrees at 10 weeks (Tronick, 1972). Visual searches are similar to adult levels, with more saccades and the majority of fixations now focused within objects (Maurer and Maurer, 1988). The infant can follow moving stimuli to mid-line (Fiorentino, 1981), although it still shows very little head movement during gaze shifts of up to 30 degrees amplitude (Goodkin, 1980).

2.4 2-3 months

The head is now mainly centred at rest (Sheridan, 1973, Fiorentino, 1981), and the infant has sufficient torque and control to lift its upper torso with arm support (Sheridan, 1973, Fiorentino, 1981). It can also roll from side to back (Griffiths, 1954).

The infant makes head movements to assist visual search about 25% of the time for 10 degree gaze shifts and all of the time for 30 degree gaze shifts (Goodkin, 1980). It is particularly attracted to human faces and its own hands (Sheridan, 1973). It can now focus its eyes at midline, and begins to converge eyes on objects moved towards its face (Sheridan, 1973, Fiorentino, 1981). It can also follow slow moving objects through 180 degrees (Fiorentino, 1981). Between 11 and 28 weeks infants show an increase in the amount of head movements made during combined eye-head smooth pursuit (Daniel and Lee, 1990). Coarse stereopsis begins to emerge over the next 3 months (Oates et al., 2005).

Limbs are now more pliable, with smoother and more continuous movements. Arm movements tend to be symmetrical, whilst legs kick independently (Sheridan, 1973). The infant begins to reach with both arms, though mostly misses (Shirley, 1933, Fiorentino, 1981). Hands are held loosely open, can be opened and closed at will, and can grasp objects placed in the hands (Sheridan, 1973, Fiorentino, 1981). However, the infant is seldom capable of regarding a grasped object (Sheridan, 1973).

2.5 3-4 months

The infant has sufficient muscle tone to hold its head and torso up, resting on its arms, and to sit with support (Shirley, 1933, Griffiths, 1954). It also has more tone in its limbs, and generally improved control over its flexor muscles (Fiorentino, 1981). There is an increased disassociation between movement in the upper and lower extremities (Fiorentino, 1981).

The eyes now follow moving objects smoothly, using neck movements where necessary (Fiorentino, 1981). Colour vision and categorisation are at an adult level (Bornstein et al., 1976), and symmetrical patterns are preferred (Fantz, 1963).

Thumb opposition begins (Bayley, 1936).

2.6 4-5 months

The infant has sufficient muscle tone and postural control to be able to sit upright with little support, rotate around the trunk, and reach forward (Shirley, 1933, Fiorentino, 1981). It can also roll from side to side (Griffiths, 1954), and from prone to supine (Fiorentino, 1981).

Visually, the infant fixates more on itself, and can be distracted from viewing stationary objects (Fiorentino, 1981).

The infant can reach forward with both arms and grasp objects in front of the face, using a palmar grasp with increased use of radial digits (Fiorentino, 1981). Partial thumb opposition is in evidence (Bayley, 1936).

2.7 5-6 months

The infant can sit with head erect and back straight, although it still requires some support (Griffiths, 1954, Sheridan, 1973, Fiorentino, 1981). Muscle tone is sufficient for it to bear weight on extended elbows, and raise itself on extended arms when laying on its front, and pull itself to sitting (Sheridan, 1973, Fiorentino, 1981). It also begins to successfully roll from back to front.

The eyes move in unison, and watch falling objects to resting place (Sheridan, 1973). Eye movements are becoming more refined, as are accommodation reflexes, conjugate movements, and depth perception (Fiorentino, 1981). The infant is visually insatiable, moving head and eyes to search for, and fixate on, novel stimuli. It will immediately fixate on small interesting objects and simultaneously reach for them (Sheridan, 1973). It is also attracted to its own hands and feet.

Two-handed grasping and reaching is predominant, but the infant may use one hand whilst holding an object with the other (Sheridan, 1973, Fiorentino, 1981). There is sufficient balance and control to enable reaching and grasping while seated, including for dangling and dropped objects (Sheridan, 1973, Fiorentino, 1981). The radial-palmar grasp emerges, and the infant is capable of passing objects from hand to hand (Sheridan, 1973, Fiorentino, 1981). It will also grasp its own feet. Wrist rotation begins to emerge (Bayley, 1936).

Sound localisation continues to improve, with the infant able to visually locate an audio source at a distance of 1.5 feet at ear level, although not in the mid-line (Sheridan, 1973).

Leg muscle tone and control continue to improve. Alternating leg movements are common, and there is sufficient control to leg-grasp objects (Sheridan, 1973). There is also sufficient tone to bear weight on the legs, but not yet enough postural control for unaided standing (Sheridan, 1973).

2.8 6-7 months

The infant can sit alone (Shirley, 1933), and roll from back to stomach (Griffiths, 1954). Thumb opposition is now complete (Bayley, 1936).

2.9 7-8 months

The infant has gained voluntary, disassociative control over most of its movements, although they still require further refinement (Fiorentino, 1981). It can sit unaided for a short time with its legs out in front, and half-kneel (Griffiths, 1954, Fiorentino, 1981). Muscle tone is sufficient to enable the infant to pull itself to standing, and stand with flat feet, although posture and balance have not developed sufficiently for free standing (Fiorentino, 1981).

The pincer grasp emerges, and infants may transfer objects bilaterally or unilaterally (Fiorentino, 1981). Voluntary release of objects also emerges, but this is very crude (Fiorentino, 1981).

Vigorous attempts are made at crawling (Griffiths, 1954), but success may be limited to crawling on its stomach (Fiorentino, 1981).

2.10 8-9 months

There is active whole body movement. Posture and balance is sufficient to be able to sit unaided for long periods, lean forward and turn to the side whilst reaching, and stand briefly with support (Sheridan, 1973). The infant is capable of pulling itself to standing, but not lower to sitting (Sheridan, 1973).

Hand-eye coordination is good, and the infant is able to manipulate objects and pass them from hand to hand (Sheridan, 1973). It grasps small objects with an inferior pincer grip, and can point and poke at objects with a single finger (Sheridan, 1973). However, the infant cannot place objects down in a controlled way, only by dropping them or pushing them against a firm surface (Sheridan, 1973).

Fast audio-visual location at 3 feet from ear above and below ear level, except near midline (Sheridan, 1973).

Further attempts are made at crawling, with some success (Griffiths, 1954). Mobility is also achieved through rolling or squirming (Sheridan, 1973). Held standing, the infant steps purposefully on alternate feet (Sheridan, 1973).

2.11 9-10 months

The infant shows independence in sitting, grasping and releasing. It can twist, turn, pivot, and regain sitting balance (Fiorentino, 1981). Standing is still achieved through pulling up on furniture (Griffiths, 1954).

Small items are grasped using the pincer grip, and finger isolation emerges (Fiorentino, 1981). More advanced hand use is demonstrated, with wrist extension and supination (Fiorentino, 1981).

Crawling or “bear walking” on hands is now achieved (Shirley, 1933, Fiorentino, 1981). The infant may walk with both hands held (Shirley, 1933, Fiorentino, 1981).

2.12 10 - 11 months

The infant may walk when led (Shirley, 1933).

2.13 11-12 months

The infant can rise to sitting position from lying down without aid (Sheridan, 1973). To stand, it still requires the support of furniture to pull itself up on (Shirley, 1933). It may stand unaided for a few moments, and can let itself down again holding onto furniture(Sheridan, 1973).

Stereopsis is now near adult levels, and the infant has good clarity in centre of the visual field (Hickley, 1977, Oates et al., 2005).

Grasping of fine objects is facilitated by a neat pincer grasp between thumb and tip of index finger (Sheridan, 1973). The infant uses both hands freely, but shows preference for one (Sheridan, 1973). It can hold two cubes, one in each hand, simultaneously, with a primitive ‘tripod’ grasp (Sheridan, 1973).

Audio-visual location is immediate, in response to hearing tests at 3-4.5 feet from the ear (Sheridan, 1973).

The infant can move around on the floor by crawling on its hands and knees, shuffling on its buttocks, or bear-walking (Griffiths, 1954, Sheridan, 1973). It can sidestep whilst holding onto furniture (Griffiths, 1954), and may walk forward with hands held, or possibly even alone (Sheridan, 1973).

3. Development sequence for a humanoid robot

The data presented in the previous section summarises infant development over the first 12 months after birth. From this, we have extracted the timings and level of development of sensor and motor systems that are applicable to our iCub robot. For example, in the previous section, neck control is described to develop over the first three months, whereas wrist control does not appear to start until month 6. As an illustration, an abstraction of the motor development sequence is shown in Fig. 1. A similar chart covering visual development is shown in Fig. 2.

As described in the previous section, infants gradually develop control of their limbs over time. This is reflected in Fig. 1 as shaded areas, which get progressively darker as a skill improves (note that the termination of a shaded bar does not indicate the termination of that skill, but that it has been sufficiently developed as to no longer appear in the literature). Abilities shown in the date column marked 'Birth' are apparent at, or very shortly after, birth; those shown in the age column labelled '1' emerge during the first month after birth. It is interesting to note that the sequence for motor development is cephalocaudal: it begins with the eyes, and progressively moves down the body, through the neck and arms, with torso and wrist control being refined last. The exception to this is the hands, which become active in the first month, but continue to develop until the tenth month.

In a robot, this gradual learning of motor skills is achieved through our constraint lifting framework. Various forms of constraint exist, and we illustrate two here: The first type constrains against the system attempting to learn a skill until the necessary prerequisites are in place. For example, the system will not be able to learn to perform a pincer grasp until the control of thumb opposition has been sufficiently established. The second type represents a restriction on resolution, accuracy, or bandwidth of a channel, with the relaxing of constraints allowing learning at a finer level. We have demonstrated both types of constraints in (Lee et al., 2007b) and (Lee et al., 2007a) respectively.

We approach the selection of constraints in the following way: an analysis of the robot system defines all the sensory, motor, and internal channels available, and also records their dimensions, parameters, and significant variables. Then a developmental sequence is drawn up, by mapping and adapting the prototype infant example onto the available modalities from the analysis (as in Fig. 1). Currently constraints are generated by hand, and here we give separate sequences for two desired actions. Analysis of the developmental sequence identifies the onset and completion of learning for the selected sensor and motor functions and combinations. Individual joint and sensor functions are initiated in thier own constraints stages in the order in which they appear in the literature. These are then combined in later stages to form aggregate actions, in accordance with the literature. The result is a table of constraints showing the incidence of individual abilities, and their gradual combination as time progresses.

For example, fig. 3 depicts a constraints architecture for learning to coordinate eye and body movements to fixate on a stimulus of interest. Here the development sequence consists of thirteen stages, beginning with learning to saccade to a stimulus, and ending with the refinement of torso yaw as an aid to fixation. At each stage constraints are in place restricting the system to a limited number of functions. Each stage also has an associated saturation criteria that, when met, triggers a change in the constraints imposed on the system. This may be an easing of constraints on a particular function, or a complete removal of a constraint. Fig. 4 depicts a similarly derived constraints sequence for learning to reach.

The constraints table is used to direct learning in the robot. Initially, the robot is constrained to the first stage and allowed to learn the correlations between the active sensor and motor systems. In our framework, sensor and motor spaces are represented as maps, populated by fields, which designate areas of equivalence on the maps. We use hebbian learning to build links, or mappings, between related fields on separate maps, and hence learn the correlation between sensor and motor spaces. Learning of mappings is driven by novelty, with the robot repeating actions that result in novel changes in sensory spaces. Eventually, the robot will have investigated the available space, and learning will saturate. A measure of habituation triggers the removal or relaxation of a constraint, resulting in a stage transition or improvement of resolution. The learning cycle then begins again. A detailed description of the constraints releasing framework can be found in (Lee et al., 2007a) and (Lee et al., 2007b).

The stages indicated in these constraints systems are not fixed in their order, nor are they triggered in isolation. Some stages may be learnt in parallel, and similar levels of development may appear in different orders, although the system will follow the general time line for infant development. Importantly, the constraints do not directly control the developmental stages, but simply release more complexity to the learning processes. Thus stage transitions are emergent; their ordering and timing are not easily predictable. Indeed, the system may even regress to earlier stages when an action cannot be successfully learned due to gaps in the system's previous experience. Although some stage transitions will be programmed, others may occur without any intervention: the interaction of the various systems naturally limiting or promoting further development.

We have previously demonstrated our constraints lifting framework as applied to individual stage transitions (Lee et al., 2007b). The work here goes further by describing how to scale up the constraints-based approach to a robot with many more degrees of freedom, and with more sensing abilities, based on the infant development time line. We are implementing these systems in our ongoing work.

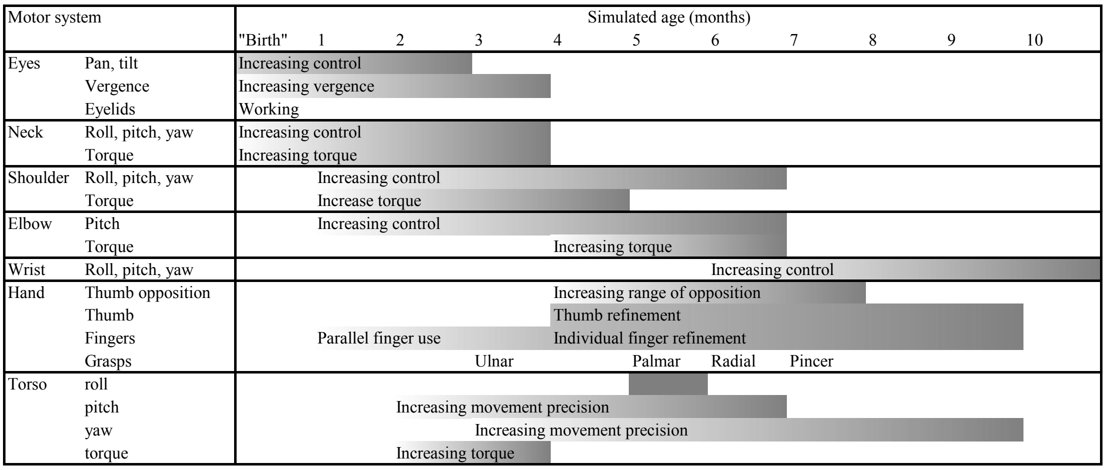

Figure 1: Partial motor development sequence for a humanoid robot. Shaded regions relate to periods of development of each ability as observed in infants. Darker shading indicates more advanced ability.

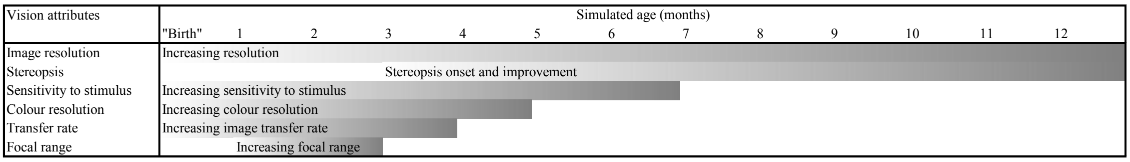

Figure 2: Partial vision development sequence for a humanoid robot.

4. Conclusion

The "Embodied Intelligence" approach to building artificial cognitive systems argues that the nature of the physical hardware of a robot is an essential factor in determining both its behaviour and the extent of its cognitive abilities. In addition "Developmental Robotics" dictates that early experience provides a vital grounding for later competencies. Taken together, we see that to attain even approximate human levels of cognition and learning, we should work towards models of developmental learning on robot platforms with humanoid structure. This paper has described part of our research in a programme that aims to demonstrate autonomous cognitive growth on an iCub humanoid robot. While developmental robotics research often refers to the findings of Piaget and others, and sometimes acknowledges the cephalo-caudal flow of development, we propose that knowledge of the finer patterns of development and the associated constraints will provide an understanding of robot shaping that will have wide applicability to robotics research.

Acknowledgements

This research was supported by 'IM-CLeVeR', European Commission grant no. FP7-ICT-IP-231722.

References

Adams, R. J., Courage, M. L., and Mercer, M. E. (1994). Systematic measurement of human neonatal color vision. *Vision Research*, 34:1691–1701.

Asada, M., Hosoda, K., Kuniyoshi, Y., Ishiguro, H., Inui, T., Yoshikawa, Y., Ogino, M., and Yoshida, C. (2009). Cognitive developmental robotics: A survey. *IEEE Transactions on Autonomous Mental Development*, 1(1):12–34.

Bayley, N. (1936). The development of motor abilities during the first three years: A study of sixty-one infants tested repeatedly. *Monographs of the Society for Research in Child Development*, 1(1):1–26.

Bornstein, M. H., Kessen, W., and Weiskopf, S. (1976). The categories of hue in infancy. *Science*, 191:201–202.

Bruner, J. (1990). *Acts of Meaning*. Harvard University Press, Cambridge, MA.

Bushnell, I. W. R. (2001). Mother's face recognition in newborn infants: Learning and memory. *Infant and Child development*, 10:67–74.

Developmental stage	"Age" (months)	Eyes: tilt	Eyes: version	Eyes: vergence	Neck: pitch	Neck: roll	Neck: yaw	Neck: torque	Torso: roll	Torso: pitch	Torso: yaw	Torso: torque	Saturation criteria	Observed behaviour
1 Eye saccade	0	d	d										Low occurance of unknown saccades	Eye saccades to fixate on stimuli
2 Vergence	0			d									Low occurance of unknown vergence movements	Both eyes converge onto a single stimuli
3 Neck movements	0				d	d	d	d					Low occurence of unknown movements	Neck roll pitch and yaw movements
4 Eye & head visual search	0	d	d	d	d	d	d	d					Low occurance of unknown combinations of movements	Head and eyes move together to fixate on a stimulus
5 Torso pitch	2									d		d	Low occurence of unknown movements	Torso bends foraward and backward
6 Eye, head & torso pitch visual search	2	d	d	d	d	d	d	d		d		d	Low occurance of unknown combinations of movements	Fixations incorporate bending movements at the waist
7 Torso pitch & yaw	3									d	d	d	Low occurence of unknown movements	Torso bends forwards, backwards, and sideways at waist
8 Eye, head & torso pitch & roll visual search	3	x	x	d	d	d	d	d		d	d	d	Low occurance of unknown combinations of movements	Fixations incorporate bending and leaning movements
9 Eye, head & torso pitch & roll visual search	4	x	x	x	x	x	x	x		d	d	x	Few improvements in eye and neck movements	Looking whilst bending and leaning
10 Torso roll, pitch & yaw	5								x	d	d	x	Low occurence of unknown movements	Torso bends, leans and rotates at waist
11 Full body visual search	5	x	x	x	x	x	x	x	x	d	d	x	Low occurance of unknown combinations of movements	Looking with whole body movement
12 Improvement of torso pitch	7	x	x	x	x	x	x	x	x	x	d	x	Few improvements in torso pitch	Less jerky bending movement whilst looking
13 Improvement of torso yaw	10	x	x	x	x	x	x	x	x	x	x	x	Few improvements in torso yaw	Smoother body rotation whilst looking

Figure 3: Constraints architecture for staged development of visual fixation coordinated with eye, head, and body movements. At each stage the system is constrained so that it only has access to systems marked 'd' or 'x', where 'd' denotes a system under development, and 'x' is a fully developed system.

Butterworth, G. and Harris, M. (1994). *Principles of Developmental Psychology.* Lawrence Erlbaum Associates, Hove.

Daniel, B. M. and Lee, D. N. (1990). Development of looking with head and eyes. *Journal of Experimental Child Psychology*, 50:200–216.

De Casper, A. J. and Fifer, W. (1980). Of human bonding: Newborns prefer their mothers' voices. *Science*, 208:1174–1176.

Erez, T. and Smart, W. D. (2008). What does shaping mean for computational reinforcement learning? In *Proc. ICDL*, pages 215–219.

Fantz, R. L. (1963). Pattern vision in newborn infants. *Science*, 140:296–297.

Field, T. M., Cohen, D., Garcia, R., and Greenburg, R. (1984). Mother-stranger face discrimination by the newborn. *Infant Behaviour and Development*, 7:19–25.

Fiorentino, M. R. (1981). *A Basis for Sensorimotor Development, Normal and Abnormal: The Influence of Primitive, Postural Reflexes on the Development and Distribution of Tone.* Charles C Thomas, Springfield, Ill.

Goodkin, F. (1980). The development of mature patterns of headeye coordination in the human infant. *Early Human Development*, 4:373–386.

Griffiths, R. (1954). *The abilities of babies.* University of London Press, London.

Hainline, L. (1998). How the visual system develops. In Slater, A., (Ed.), *Perceptual development:Visual, auditory, and speech perception in infancy*, pages 5–50. Psychology Press.

Hickley, T. L. (1977). Postnatal development of the human lateral geniculate nucleus: relationship to a critical period for the visual system. *Science*, 198:836–838.

Illingworth, R. S. (1983). *The development of the infant and young child.* Churchill Livingstone, Edinburgh.

Kellman, P. J. and Arterberry, M. E. (1998). *The cradle of knowledge: Development of perception in infancy.* MIT Press, Cambridge, MA.

Lee, M., Meng, Q., and Chao, F. (2007a). Developmental learning for autonomous robots. *Robotics and Autonomous Systems*, 55(9):750–759.

Lee, M., Meng, Q., and Chao, F. (2007b). Staged competence learning in developmental robotics. *Adaptive Behaviour*, 15(3):241–255.

Lungarella, M., Metta, G., Pfeifer, R., and Sandini, G. (2003). Developmental robotics: a survey. *Connection Science*, 15(4):151–190.

Developmental stage	"Age" (months)	Shoulder pitch	Shoulder roll	Shoulder yaw	Shoulder torque	Elbow pitch	Elbow torque	Wrist roll	Wrist pitch	Wrist yaw	Torso roll	Torso pitch	Torso yaw	Torso torque	Saturation criteria	Observed behaviour
1 Shoulder movements	2	d	d	d	d										Low occurence of unknown movements	Arm moves in all directions from shoulder
2 Elbow movements	2					d									Low occurence of unknown movements	Onset of elbow movement
3 Shoulder and elbow movements	2	d	d	d	d	d									Low occurance of unknown combinations of movements	Weak, unrefined, combined shoulder and elbow movements
4 Torso pitch	2											d		d	Low occurence of unknown movements	Torso bends foraward and backward
5 Reaching while bending	2	d	d	d	d	d						d		d	Low occurance of unknown combinations of movements	Reaching while bending at waist
6 Torso pitch and yaw	3											d	d	d	Low occurence of unknown movements	Torso bends forwards, backwards and sideways at waist
7 Reaching with torso pitch and yaw	3	d	d	d	d	d						d	d	d	Low occurance of unknown combinations of movements	Reaching while bending and leaning from waist
8 Improved torso torque	4	d	d	d	d	d	d					d	d	x	Low occurence of unknown movements	Stronger movements in elbow and waist
9 Torso roll, pitch and yaw	5										x	d	d	x	Low occurence of unknown movements	Torso bends, leans and rotates at waist
10 Reaching with torso movement	5	d	d	d	x	d	d				x	d	d	x	Low occurance of unknown combinations of movements	Reaching whilst bending, leaning and turning
11 Wrist movement	6							d	d	d					Low occurence of unknown movements	Onset of wrist movement
12 Whole arm reach with body movement	6	d	d	d	x	d	d	d	d	d	x	d	d	x	Low occurance of unknown combinations of movements	Unrefined full arm manipulation
13 Arm refinement	7	x	x	x	x	x	x	d	d	d	x	x	d	x	Few improvements in elbow and shoulder movements	Refined full arm manipulation
14 Developed torso yaw	10	x	x	x	x	x	x	d	d	d	x	x	x	x	Few improvements in torso yaw	Refined torso yaw
15 Complete reach	11	x	x	x	x	x	x	x	x	x	x	x	x	x	Few improvements in wrist movements	Fully developed reaching

Figure 4: Constraints architecture for staged development of reaching motions. Although not indicated, the elbow has minimal torque sufficient to allow limited motion until it begins to develop at stage 8.

MacFarlane, A. (1975). Olfaction in the development of social preferences in the human neonate. In *Parent Infant Interaction (CIBA Foundation Symposium 33)*. Elsevier, Amsterdam.

Maurer, D. and Maurer, C. (1988). *The World of the Newborn*. Basic Books, New York.

Metta, G., Sandini, G., Vernon, D., Natale, L., and Nori, F. (2008). The icub humanoid robot: an open platform for research in embodied cognition. In *Performance Metrics for Intelligent Systems Workshop*, Washington DC, USA.

Muir, D. and Field, J. (1979). Newborn infants orient to sounds. *Child Development*, 50:431–436.

Oates, J., Wood, C., and Grayson, A. (2005). *Psychological Development and Early Childhood*. Blackwell Publishing, Malden, MA.

Rutkowska, J. (1994). Scaling up sensorimotor systems: Constraints from human infancy. *Adaptive Behaviour*, 2:349–373.

Schlesinger, M., Parisi, D., and Langer, J. (2000). Learning to reach by constraining the movement search space. *Developmental Science*, 3(1):67–80.

Sheridan, M. D. (1973). *From Birth to Five Years*. Childern's Developmental Progress. NFER-NELSON, Windsor.

Shirley, M. M. (1933). *The First Two Years - A Study of Twenty-five Babies*, volume 2 of *Intellectual Development*. University of Minnesota Press, Minneapolis.

Steiner, J. (1979). Human facial expression in response to taste and smell stimulation. *Advances in Child Development and Behaviour*, 13:257–295.

Stoytchev, A. (2009). Some basic principles of developmental robotics. *Autonomous Mental Development, IEEE Transactions on*, 1(2):122 – 130.

Tronick, E. (1972). Stimulus control and the growth of the infant's effective visual field. *Perception & Psychophysics*, 11(5):373–376.