

Agent-Based Models of Levels of Consciousness

Helena Hong Gao
John H. Holland

SFI WORKING PAPER: 2008-12-048

SFI Working Papers contain accounts of scientific work of the author(s) and do not necessarily represent the views of the Santa Fe Institute. We accept papers intended for publication in peer-reviewed journals or proceedings volumes, but not papers that have already appeared in print. Except for papers by our external faculty, papers must be based on work done at SFI, inspired by an invited visit to or collaboration at SFI, or funded by an SFI grant.

©NOTICE: This working paper is included by permission of the contributing author(s) as a means to ensure timely distribution of the scholarly and technical work on a non-commercial basis. Copyright and all rights therein are maintained by the author(s). It is understood that all persons copying this information will adhere to the terms and constraints invoked by each author's copyright. These works may be reposted only with the explicit permission of the copyright holder.

www.santafe.edu



SANTA FE INSTITUTE

Agent-based Models of Levels of Consciousness

Helena H. Gao and John H. Holland
Nanyang Technological University and University of Michigan

Abstract

This paper is based on recent interdisciplinary experimental studies that emphasize the steps in language acquisition during the first few years of life. These steps are characterized as changes in levels of consciousness. The object is to place successive levels of consciousness in a *complex adaptive systems (cas)* framework, a framework that centers on learning agents that interact via exchanges of signals such as gestures and utterances. The *cas* framework thus provides a strong emphasis on the social nature of language acquisition and evolution. The models described are exploratory, not predictive. As such, the models are meant to suggest new mechanisms and experiments that will increase our understanding of language.

Overview.

The overall object of this line of research is to develop an interlocking series of rule-based models that serve as simple examples of successive levels of consciousness. The underlying approach is developmental, relating acquisition to the increasing autonomy and disembodiment of a newborn in social interactions. This autonomy depends upon the ability of a complex adaptive system (*cas*) – a system with many feedback loops – to have ongoing interior activity that is modulated, but not determined, by current stimuli.

We are particularly interested in procedures that use established behavioral rules as the basis for the formation of new rules that implement progressive disembodiment and autonomy. The new rules should be woven into an increasingly sophisticated internal model that allows a learning agent to plan ahead. Such planning is critical to anticipating future effects of current actions. In language acquisition, the internal model allows the learning agent to determine what future utterances will fit grammatically with current utterances.

An important part of our outlook for generating new behavioral rules is the idea that new rules can be formed by combining building blocks extracted from rules already established. This procedure involves operations similar to those that breeders use in crossbreeding to get more sophisticated varieties.

Prologue.

The newborn receives an incredible amount of stimulation. In the retina alone there are roughly 1,000,000 light sensitive neurons firing dozens of times a second. Moreover, inevitable variation in incoming light levels means that no firing pattern ever exactly repeats – there is perpetual novelty in the input. Similar comments apply to other sensory modes. Far from a poverty of stimuli, the infant faces a torrent of stimuli. The only way to handle this perpetual novelty is to extract and respond to regularities and patterns. More formally, the newborn must find equivalence classes that correspond to repeating patterns.

There is some wired-in help in this task, supplied by a long evolutionary history. The newborn can respond to a few selected patterns, such as a mother's smile. Rather remarkably there is even circuitry connecting this incoming pattern to muscles around the mouth, allowing the newborn to imitate the smile! But how does the newborn go on from there to make sense of the torrent of novel input? In particular, how does the newborn travel the long distance from initial, very limited abilities to language acquisition?

Language acquisition is such a complex process that there is a large gap between data and an explanation of the processes that generate the data. Models and theory can help close this gap, but the path can be difficult. To see something of the difficulties, consider a much earlier example of this transition from data to theory: For millennia humans had observed and speculated about the movement of inanimate objects, ranging from falling stones to flying arrows and the movement of planets. Fallacious "laws" were common: "a moving object always comes to rest", "heavier objects fall faster", and so on. All the while, the list of observations and examples grew longer. Newton's simple laws brought this diverse array of observations within a common framework that both predicted what would happen in unfamiliar situations and made control possible. The framework also fostered new methods of teaching (e.g., general principles of fluid flow) and new artifacts (e.g., turbines). It is unlikely that simple laws will encompass language acquisition, but even a rudimentary theory should offer similar advantages in, say, second language teaching and automatic language translation.

One way to build a unifying framework is to single out prototypes and extract the mechanisms that make them work. Going again to a physical analogy, we use gears and springs to understand the working principles of everything from watches to wagons. We even speak of a "clockwork universe" as a way of getting a better understanding of causality. What, then, are the prototypes for different levels of linguistic ability?

In a newborn, language development certainly depends upon an expanding consciousness, but "consciousness", like "life" or "mind", is difficult to define precisely. Still, there are well-developed sciences that center on life and mind – biology and psychology – so we should not be too quick to dismiss an approach to language acquisition centering on consciousness. The relation between language and consciousness has been discussed explicitly and implicitly over the centuries. The following quotes give a bit of the flavor:

"He gave man speech, and speech created thought, which is the measure of the universe." Percy Bysshe Shelley (1792 - 1822)

"Speech was given to man to disguise his thoughts. [La parole a ete donnee a l'homme pour deguiser sa pensee.] " Charles Maurice de Talleyrand-Perigord (1754 - 1838)

"Speech was given to the ordinary sort of men, whereby to communicate their mind; but to wise men, whereby to conceal it." Robert South (1634 - 1716)

"Men use thought only to justify their wrong doings, and employ speech only to conceal their thoughts. [Ils ne se servent de la pensee que pour autoriser leurs injustices, et emploient les paroles que pour deguiser leurs pensees.] " Francois Marie Arouet Voltaire (1694 - 1778)

In these quotations, consciousness is implicitly discussed as thought expressed in language. Even further back, in Plato's time, there was a general agreement that one can only speak of what one is consciously aware. Nowadays, however, linguistic theories rarely touch upon consciousness. Chomsky's (1965) theory of universal grammar is a case in point. Chomsky holds that all children are born with an innate grammar based on mental transformational rules. This innate grammar enables a child to originate sentences not previously heard. Though the child employs mental rules there is no discussion of what mental activities impel a child to create a novel sentence. A fortiori, in Chomsky's view, there is no role for consciousness in activating these rules.

However, recent cross-disciplinary research does open a channel for researchers to discuss consciousness in relation to language. One can see the language function as a tool for reporting conscious experiences. Peter Carruthers (1996, 2000), for instance argues that much of conscious thinking takes place in natural language. On this view, a better understanding of consciousness contributes to a better understanding of language and vice versa. Certainly, consciousness does not exist on its own; its existence becomes observable only when other mental activities are actively involved, such as conscious body movement vs. unconscious body movement, conscious utterance vs. unconscious utterance, and conscious thought vs. unconscious thought. Therefore, consciousness is to a large extent revealed by other types of mental phenomena that together make one's mental life as a whole.

The approach we take here relates different levels of consciousness to well-known transitions in physiological and mental control as the newborn develops (Zelazo, 2004). We will distinguish mechanisms (behavioral traits) that generate the behaviors at different levels of consciousness. Following Braitenberg's (1984) *Vehicles, Experiments in Synthetic Psychology*, we will select mechanisms at each level that mesh smoothly with the mechanisms adduced for earlier levels. Ultimately this framework should suggest new experiments and, even, new approaches to teaching language.

Levels of Consciousness (LoC).

Personal construct theory (Kelly, 1955/1991) defines human consciousness as undergoing both conscious and unconscious processes. It postulates human cognition as starting from unconscious processes, or "low levels of cognitive awareness". These fundamental concepts of consciousness form the basic understanding of how human beings develop as social beings.

According to Zelazo's (2004) levels of consciousness (LoC) model, the characteristics of children's development of consciousness undergo various levels of what Kelly termed "conscious processes" before the child reaches full linguistic capability. The age-related increases in LoC are related to the quality of experience, the potential for recall, the complexity of children's explicit knowledge structures, and the possibility of the conscious control of thought, emotion, and action. The basic assumption of the LoC model is that children's consciousness has several dissociable levels of consciousness – information can be available at one level but not at others. This differs from models mainly based on adult data that distinguish between consciousness and a meta-level of consciousness (e.g. Schooler, Schachter, and Moscovitch). With the LoC model, consciousness is hierarchically arranged, and it is possible to observe the level at which consciousness is operating in specific situations.

Based on the central claim, LoC models make the following assumptions of the age-related changes in executive functions as children develop:

LoC 0 Unconscious activities: Inherited ('wired in') cognitive abilities.

Pre-primate precursors to language acquisition:

- (i) Ability to imitate utterances and gestures.
- (ii) Ability to distinguish between objects and actions.
- (iii) Awareness of a mutually apprehended salient object or action.
- (iv) Basic learning procedures (akin to Hebb's learning rule).

LoC 1 Minimal consciousness: Innate reinforcement of repeatable activities, ranging from repetition of sounds and motions to actions that produce innate rewards.

Example: Directed motion of hand across visual field (a precursor to gesture).

LoC 2 Stimulus-response (conditioned) consciousness: Labeling from semantic long-term memory.

Example: Utterances that cause innate rewards (such as causing mother to smile).

LoC 3 Simple recursive consciousness: Use of labels (utterances) to cause others to act (such as causing mother to fetch a bottle).

Example: Utterances that lead to food acquisition when food visible.

LoC 4 Extended recursive consciousness: Use of labels to cause others to act when object is not present.

Example: Food acquisition when food not visible.

LoC 5 Self-consciousness: Use of labels facilitate planned sequences of action (e.g. sequenced utterances), characterize mental activities of others, to look ahead and explore alternative courses of action.

Example: Distinguish between two similar objects using a sequenced pair of utterances.

Newborn babies are assumed to experience minimal consciousness (LoC1) (cf. Armstrong, 1980). LoC1 is the simplest, but still conceptually coherent, consciousness that accounts for the behavioral evidence. However, LoC1 is unreflective, present-oriented, and makes no reference to a concept of self. So, in LoC1, one is conscious of what one sees (the object of experience), but not of seeing what one sees, let alone that one's 'self' is seeing what one sees. As a consequence, one cannot recall seeing what one saw. LoC1 infant behavior lasts till the end of the first year.

Numerous new abilities appear within months, such as starting to utter words, using objects in a functional way, pointing proto-declaratively, and searching flexibly for hidden objects. The infant works through conditioned consciousness (LoC2) to a new form of consciousness – recursive consciousness (LoC3), observed in 2-year-olds. LoC3 is marked by two signs: (i) the existence of a perceptual experience and (ii) the ability of labeling from semantic long-term memory. For instance, if a 1-year-old toddler says 'dog', it is assumed that the infant successfully combines a perceptual experience with a label from semantic long-term memory. The existence of labeling makes the contents of minimal consciousness perceptible and recoverable, and thus provides an enduring trace of the experience of certain content. This trace lasts long enough to be deposited into both long-term memory and working memory. The contents of working memory (e.g.

representations of hidden objects) can then serve as goals to trigger action programs indirectly so the toddler is not restricted to responses triggered directly by minimal and conditioned (LoC1 & 2) experience of an immediately present stimulus.

In contrast to 2-year-olds, 3-year-olds do not persevere on a single rule when provided with a pair of rules to use. However, there are still limitations on 3-year-olds' executive function, as seen in their perseveration in the Dimensional Change Card Sort (Zelazo, 2006), which represents the integration of two incompatible pairs of rules into a single structure. The Dimensional Change Card Sort requires children to adopt an even higher LoC, extended recursive consciousness (LoC4): Evidence indicates that this LoC first emerges by around 4 years of age, together with a range of metacognitive skills studied under the rubric of 'theory of mind' (Frye, et al., 1995; Perner, & Lang, 1999; Carlson, & Moses, 2001).

As William James (1901) suggested that an understanding of consciousness would provide the key to intellectual accomplishment, children's awareness of Self is seen as a major developmental transition that begins at the end of the second year. Linguistically, this is marked by children's first use of personal pronouns. Cognitively, this is marked by their self-recognition in mirrors, and emotionally, by their display of self-conscious emotions such as shame. According to the LoC model, this transition is brought about by another LoC, referred to as self consciousness (LoC5).

According to Zelazo, et al. (2007), increases in the level of consciousness that children must be brought about by the re-processing of experienced information via neural circuits in prefrontal cortex. The potential for recall, the complexity of knowledge structures, and the possibility of action control all increase. Reprocessing adds depth to subjective experience because more details can be integrated into the experience before the contents of consciousness are replaced by new environmental stimulation. Each degree of reprocessing causes information to be processed at a deeper, less superficial level, which increases the likelihood of retrieval (Craik, & Tulving, 1975). Higher LoC make possible more complex knowledge structures, increasing the scope of cognitive control. This advance, in turn, moves consciousness away from stimuli and responses, making possible, more decontextualized discursive reasoning.

These transitions result in increasing autonomy for the infant. The autonomy shows itself first in conditioning that provides the infant with responses based on experience. Then anticipation and short-term planning follow and, finally, internal models that allow planning and lookahead (as in playing a game of chess). Each stage is closely related to progression in control of utterances and, ultimately, organized meaningful sequences of utterances. In short, we will claim that this increasing autonomy marks progressive changes in linguistic ability.

Experiments.

The need for different LoC's for a knowledge/action dissociation is illustrated by experiments done by Zelazo and his group of researchers with different versions of the Dimensional Change Card Sort (DCCS). In a typical experiment, children are shown two target cards (e.g. a blue rabbit and a red car) and asked to sort a series of bivalent test cards (e.g. red rabbits and blue cars) according to one dimension (e.g. color). Then, after sorting several cards, children are told to stop playing the first game and switch to another (e.g. shape), 'Put the rabbits here; put the cars there.'). Regardless of which dimension is presented first, 3-year-olds typically

continue to sort by that dimension despite being told the new rules on every trial (e.g. Frye, et al., 1995, Jacques, S. et al., 1999, Perner, J., & Lang, B., 2002, Brooks, P.J. et al., 2003). By contrast, 4-year-olds recognize immediately that there are two sets of rules for the game and a switch of rules is needed regarding shape or color.

The example shows that the two groups of children, 3-year-olds and 4-year-olds, are at different stages of conscious development. For 3-year-olds, understanding a set of rules at a time, doesn't seem to be a problem. But, once a new set of rules is introduced, children at this age are found to be unable to switch back and forth. They seem to be unable to represent the rules at a higher LoC, a level which allows them to make a deliberate decision to follow either the pre-switch rules or the post-switch rules. For 4-year-olds, the two ways of construing the stimuli are perceived as a reflection of multiple perspectives on the situation. Such understanding can only happen at a higher LoC because, as Figure 1b in Zelazo (2004) indicates, that level allows an integration of the different rules into a more complex rule structure.

There are numerous examples of age-related changes in children's ability to disengage from a compelling construal of a situation. For example, children become more likely, over the course of the second year, to perform pretend actions (e.g., talking on the telephone) with pretend objects (e.g., a spoon) that bear little physical resemblance to the real objects. They also become more likely to perform pretend actions without objects altogether (e.g., Ungerer, et al., 1981). Similar changes continue into the preschool years (Overton, & Jackson, 1973; O'Reilly, 1995). As these changes occur, there are complementary changes in children's ability to resist responding with actions suggested by the objects (e.g., putting the spoon into the mouth). See Elder, & Pederson, 1978; Pederson, Rook-Green, & Elder, 1981.

This general development pattern—from stimulus-dependent to cognitively-controlled activity – we identify with changes in level of consciousness. In the A-not-B task (Piaget, 1954; Marcovitch, & Zelazo, 1999), 9-month-old infants watch as an object is hidden conspicuously at one of two locations, then they retrieve it. When the object is then hidden at a new location, 9-month-olds are likely to search for it at the first location. Older children, rather than responding in a perseverative, stimulus-bound fashion, evidently use an updated representation of the object's location to guide their search,

Gradually, linguistic meaning comes to dominate sensori-motor experience, as described by Vygotsky (e.g., 1978) and Luria (e.g., 1961). A recent study of 3- to 5-year-olds' flexible understanding of the adjectives "big" and "little" (Gao, et al. , 2005) provides a good example. When shown a medium sized square together with a larger one, 3-year-olds had little difficulty answering the question, "Which one of these two squares is a big one?" However, when the medium square was then paired with a smaller one, and children were asked the same question, only 5-year-olds reliably indicated that the medium square was now the big one. This example shows an age-related increase in children's sensitivity to linguistic meaning when it conflicts with children's immediate experience. It reveals that interpretation becomes progressively decoupled, from perseverative stimulus properties.

Increasing sensitivity to linguistic information is also seen in children's difficulty in interpreting ambiguous adjectives. Preliminary research (Gao, & Zelazo 2008) indicates that 3-year olds shown medium-sized pictures of a rabbit and a bear, have no difficulty identifying the bear as "a big animal." However, when 3-year-olds are shown a big picture of a rabbit and a small picture

of a bear typically point to the rabbit as the “big animal”. 4-year-olds seem to sense the ambiguity in the questions; they typically hesitate and then reply in an inconsistent fashion. By 5 years of age, however, children often ask, “What do you mean? The animals here in the picture or real animals?”, and they are more likely to point to the bear. Older children are increasingly likely to use verbal input to restrict their attention to the appropriate aspects of a situation (Ebeling, & Gelman, 1988, 1994, Jacques, & Zelazo, 2005).

Language plays a causal role in helping a child to attain higher LoC. Previous research (e.g., using the Dimensional Change Card Sort and measures of children’s theory of mind; Frye, et al., 1995) suggests that 4-year-olds are capable of considering two incompatible perspectives in contradistinction, even if they do not always do so. In a recent study, Jacques, et al. (2006) presented 4- and 5-year-olds with the Flexible Item Selection Task. On each trial of this task, children are shown sets of three items designed so that one pair matches on one dimension, and a different pair matches on a different dimension (e.g., a small yellow teapot, a large yellow teapot, and a large yellow shoe; see Figure 1).

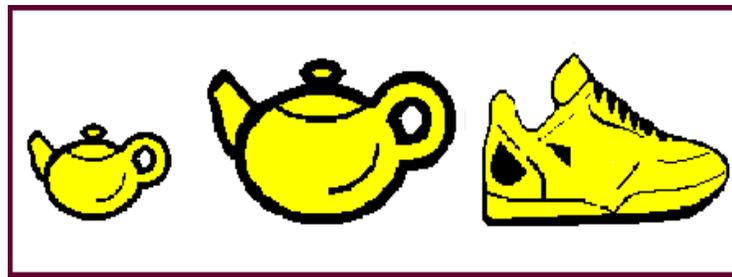


Figure 1. Flexible item selection task.

Children are first told to show the experimenter two things that go together in one way (Selection 1), and then asked to show the experimenter two things that go together in a different way (Selection 2). To respond correctly, children must represent the pivot item (i.e., the large yellow teapot) first according to one dimension (e.g., size) and then according to another (e.g., shape). Four-year-olds generally perform well on Selection 1 but poorly on Selection 2, indicating that they have difficulty thinking about the pivot item in more than one way—they have difficulty disengaging from their initial construal of the item. However, when children were asked to label the basis of their initial selection (e.g., when they were asked, “Why do those two pictures go together?”), their performance on Selection 2 improved substantially. This was true whether children provided the label themselves or whether the experimenter generated it for them.

In terms of the LoC model, labeling the perspective adopted for Selection 1 caused children to step back from that perspective and reflect on it at a higher level of consciousness. Adopting a higher level of consciousness transforms the child’s initial perspective (seeing the objects in terms of size) from a subjective frame into an object of consideration. It puts psychological distance between the child and the perspective. From the vantage point of their higher LoC, children adopt an alternative perspective (seeing the objects in terms of shape).

The adoption of higher LoC allows for both greater influence of thought on language and greater influence of language on thought. On the one hand, it allows for more effective selection and manipulation of rules (i.e., it permits the control of language in the service of thought). On the other hand, it allows for top-down structuring of interpretive frames (as in the flexible

interpretation of adjectives; Gao et al., 2005). Top-down structuring permits children to respond more appropriately to linguistic meaning despite misleading context – it allows language to influence thought. Language and thought become increasingly intertwined in a complex, reciprocal relation. Language (e.g., labeling) influences thought, by promoting a temporary ascent to a higher level of consciousness, which in turn influences language, and so on. This reciprocal relation can be seen in the growing richness of children’s semantic understanding and increasing subtlety of their word usage. Consider, for instance, a child’s developing understanding of the semantics of the verb “hit”. Children first understand hit from its use to depict simple accidental actions (e.g., an utterance by a child at 2;4.0: “Table hit head”; Gao, 2001, pp. 220). Usage is initially restricted to particular contexts. Eventually, however, reflection on this usage allows children to employ the word in flexible and creative ways (e.g., “I should hit her with a pencil and a stick”, uttered metaphorically by the same child at 3;8.6; Gao, 2001, pp. 219). As Tomasello (2000) explains, such restricted productivity requires engagement in the processes of analogy-making and structure-mapping. A child’s linguistic constructions depend on a first step of imitative learning, with some understanding of functional roles. A process of analogy-making then takes place to get to first order constructions and then later to get to higher order constructions.

These findings bring forth a central claim of the LoC framework: Increasing linguistic ability is the result of recursive processing, whereby the content of consciousness at one level is compared to other content at that same level.

An agent-based model of LoC.

Now our objective is to incorporate these observations into a theoretical framework that suggests the mechanisms underlying these LoC transitions, opening the way to new experiments. Specifically, we want to examine mechanisms that use social interactions to build new LoC on top of levels already acquired. Though the model is constrained by facts and observations, it does not try to supply parameters, such as statistical parameters, for prediction of data; it is an exploratory model.

To emphasize the role of social interaction we will use an *agent-based model* (Holland 1995). In an agent-based model, two or more agents interact through an exchange of signals, learning new behaviors as they adapt to each other. Agent-based models have been used to describe interactions in systems as different from each other as the immune system (where the signals are proteins) and markets (where the signals are buy and sell orders).

Here we will use *rule-based, signal-processing* agents (Holland et al., 1986), with rules of the form

IF (signal x is present) THEN (send signal y).

Signals x and y could be utterances, gestures, or visual input. The kinds of signals processed determine a rule’s level of performance, so that we can typically associate certain kinds of rule conditions with the LoC involved. In the following examples, T (“teacher”, e.g. the mother) stands for a competent adult that regularly interacts with the infant L (“learner”). For example, a simple rule for L might be,

IF (T lifts milk bottle) THEN (say “milk”).

Signals can also serve to coordinate internal processes, in which case they have no intrinsic meaning, serving much like the uninterpreted bit strings that coordinate instructions in a computer program. Each agent has many rules and, indeed, many rules can be active simultaneously. This simultaneous activity is roughly the counterpart of the simultaneous firing of assemblies of neurons in the central nervous system (Hebb, 1949).

(In this presentation, <action> indicates an action caused by an outgoing signal.)

Typical rule at *LoC 0* [Unconscious activities]:

IF (T utterance) **THEN** (<imitate utterance>)

(Note that L will use limited current abilities to attempt match.

E.g. T-utterance “Gloria” can become L-utterance “Do-ee”.)

Typical rule at *LoC 1* [Minimal consciousness – innate reinforcement].

IF (hand in vision cone) **THEN** (<move hand right>)

Typical rule at *LoC 2* [Stimulus-response with labeling from long-term memory].

IF (milk bottle present) **THEN** (<utterance “milk”>)

(Note that there will often be correlations between recurring patterns in the environment, such as actions and objects. These correlations can be exploited through conditioning.)

Typical rule set at *LoC 3* [Simple recursive consciousness; e.g., using utterances to cause others to act].

IF (milk bottle present) **THEN** (<utterance “milk”>)

T fetches milk bottle.

IF (milk bottle at mouth) **THEN** (<consume milk>)

Typical rule set at *LoC 4* [Extended recursive consciousness; e.g., using utterances to cause others to act on objects *not* present].

IF (hungry & no food visible) **THEN** <“milk”>

T fetches milk bottle.

IF (milk bottle at mouth) **THEN** (<consume milk>)

Typical rule set at *LoC 5* Self-consciousness [Planned sequences of action].

IF (red ball present and blue ball present) **THEN** (internal signal x)

IF (internal signal x & red ball desired) **THEN** (internal signal y & <“red”>)

IF (internal signal x & internal signal y) **THEN** (<“ball”>)

(Note that this set of rules only allows the object word “ball” to be uttered *after* the modifier “red” – a simple form of proto-grammar.)

In order for the agent to learn it must have the ability to modify its signal-processing rules. Such rule-modifying, learning abilities are innate capacities supplied by evolution. Learning abilities can also be expressed as rules – think of Hebb’s (1949) learning rule in neuro-psychology – so it is important to distinguish these meta-rules for learning from the signal-processing rules that are the grist for the meta-rules. In agent-based models, the meta-rules are unchanging and common to all agents.

For present purposes, the LoC models are based on meta-rules that are demonstrably available to pre-primates. That is, the meta-rules are not language specific. There are two general learning tasks the agent must be able to carry out:

i) Credit-assignment.

As an agent interacts it must be able to decide which of its rules are helpful and which are detrimental. At higher LoC the agent must even be able to determine which early-acting, stage-setting rules make possible later beneficial outcomes. (As an example, consider the sacrifice of a piece in a game like checkers in order to make a triple jump later.) Behavioral rules can be assigned strengths that reflect their usefulness to the system, useful rules having high strengths. Rules then compete to control the agent, strong rules winning the competition. Note that rules in this system are treated as hypotheses to be progressively confirmed or disconfirmed. (See Holland 1998, chapter 4).

ii) Rule discovery.

Once behavioral rules have been rated by credit-assignment, it makes sense to generate new rules (hypotheses) to replace rules that have little or no strength. Random generation of new rules is not an option here; that would be like trying to improve a computer program by inserting random instructions. Instead, newly generated rules must somehow be plausible hypotheses in terms of experience already accumulated. (See Holland 1995, chapter 2).

Requirement (ii) leads us to the final topic of this section, *building blocks* (Holland 1995, chapter 1 ff). Building blocks (*generators* in mathematics) have a familiar role in the sciences, best exemplified by the building block hierarchy of the physical sciences – the quark / nucleon / atom / molecule / membrane / ... hierarchy. Selected combinations of building blocks at one level form the building blocks of the next level. For example, selected nucleons can be combined, much like children's building blocks, to yield the 92 atoms of classical physics. The atoms can in turn be combined to yield a vast array of molecules; the laws that constrain the combination of atoms were originally set out in the periodic table of the elements. Each level of the hierarchy can be understood in the same way. For spoken language there is a similar a phoneme / word / sentence hierarchy. A grammar specifies the laws that determine how words can be combined to yield sentences. As with atoms, a relatively small number of words, under the compact rules supplied by a grammar, can yield a vast array of sentences.

An important advantage of building blocks in the study of LoC is that the building blocks occur as repeated patterns in the ever-changing torrent of sensory input. That is, the building blocks provide repeatable experiences in a perpetually novel environment. The human face provides a clear example of the extraction and combination of building blocks to provide simple descriptions of complex objects. Indeed the highly variable pattern that we call a "face" can be represented by the combination of just a few building blocks, as exemplified by the "smiley face" emoticon ☺. By adding a few more building blocks we can describe an astonishing array of individual faces. To see this possibility, divide the face into 10 "features": "hair style", "forehead shape", "eye shape", and so on (see Fig. 2). Allow 10 alternatives for each feature. There are thus 100 building blocks in total. By selecting one alternative for each feature, we can form a complete face. 10 billion distinct faces can be formed in that way. Other important sensory inputs can be treated similarly. Moreover, these building blocks can be arrayed in an LoC hierarchy, similar to the hierarchy in the physical sciences.

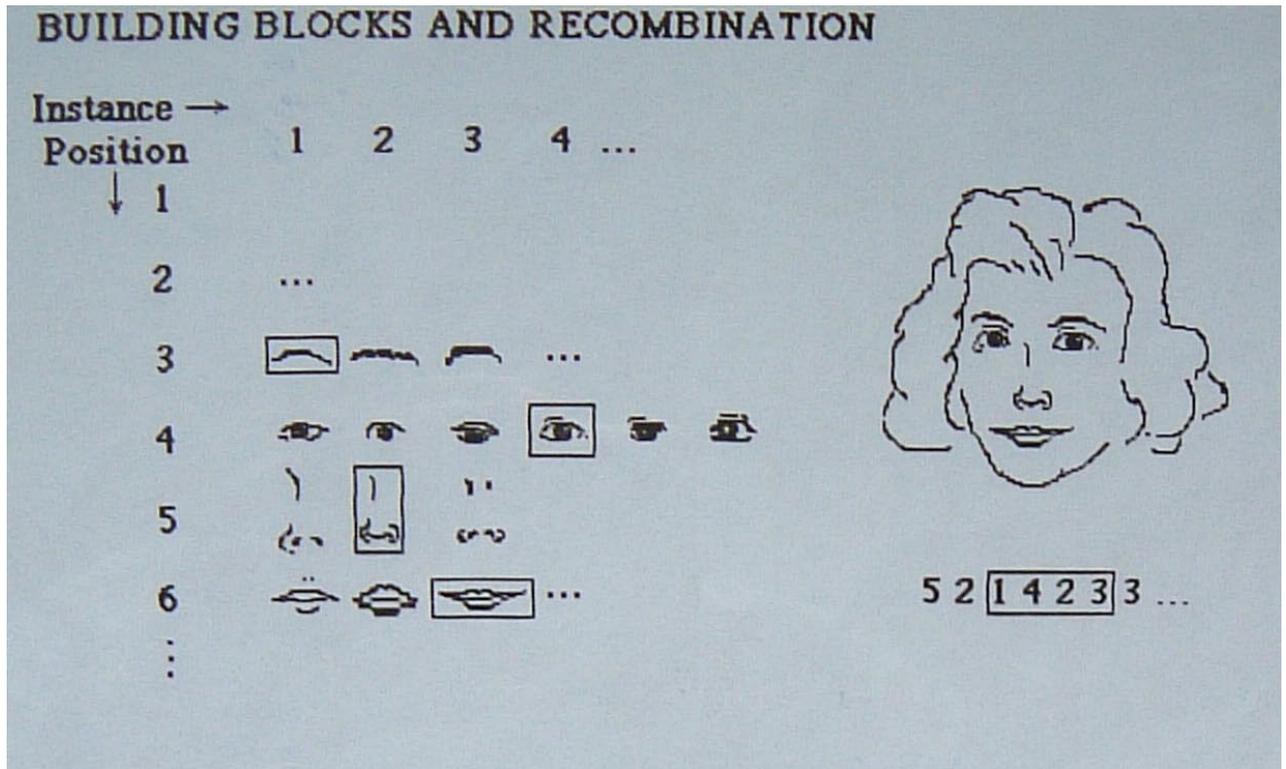


Figure 2. Building blocks.

When a building block is repeatedly associated with a rewarding event, such as food or a mother’s smile, it becomes a sampled regularity that is associated with valuable experience. From the sampling point of view, the building block’s reliability is continually tested under the credit assignment procedure. A confirmed building block becomes a plausible hypothesis when combined with other similarly distilled building blocks.

The random variation and imitation that accompany the earliest LoC provide a random sampling that helps uncover the most primitive building blocks, say phoneme-like utterances. Plausible new conditions and rules are generated by recombining building blocks already confirmed. The procedure is much like the crossbreeding of good plants (or animals) to get better plants. There is a substantial literature, centering on *genetic algorithms* (Holland 1995), that discusses the production of new rules in agent-based models via the crossing extant rules. There is not space here to discuss genetic algorithms in detail, but they are well-established procedures.

The meta-rules for credit assignment and rule discovery allow the neonate to achieve a gradual increase in control, corresponding to increasing LoC. The process begins with the acquisition of repeatable sound and gestures. Sounds and gestures reinforced by T become the building blocks for more complex utterances and gestures. For example, various combinations of 2 utterances, 3 utterances, and so on, provide substantial refinements in expression and meaning. The utterance “milk”, at the child’s single utterance stage, can have a variety of meanings: “give me some milk”, “look at the milk bottle over there”, and so on. Combining the two utterances “give” and “milk” greatly reduces this ambiguity. In mathematical terms we refine a broad equivalence class into a set of smaller, more informative sub-classes.

In this way, selected combinations of building blocks at one LoC become the building blocks for the next level. Building blocks, like grammars, offer combinatoric possibilities: a large variety of useful or meaningful structures can be constructed from a small number of building blocks. Moving up the LoC hierarchy thus becomes a much more efficient process than trying to “establish” a monolithic rule for each possibility at the highest LoC.

The discussion of credit assignment above pointed up the importance of strengthening “stage-setting” rules. Stage-setting, provided by the self-consciousness of Loc5, is the very essence of planning and autonomy. Autonomy of this kind requires that the agent be able to explore alternatives internally, without taking overt action. Rules so organized constitute an *internal model*. An agent with an internal model can internally explore sequences of action until a sequence leading to a desired outcome is located. Because the agent is dealing with sequences not yet executed, the first act of the selected sequence may not be obviously related to the last act in the sequence. This is particularly true for “stage-setting” acts: An agent may give up a piece in checkers to accomplish a later triple jump, or the agent may utter the first word of a sentence in preparation for a later utterance that will clarify a communication. Once the first act in the sequence is executed it causes a change in the environment and constrains what act(s) may be taken thereafter. The rule set for the LoC5 example exhibits a case where the first rule executed produces an utterance which constrains what kind of utterance may follow. The study of internal models in a rule-based system is presented in *Induction* (Holland et al., 1986).

Summary.

This paper is closely related to the manifesto produced by the “The Five Graces Group” at the Santa Fe Institute (to appear in LANGUAGE LEARNING). In particular, it explores the idea “that patterns of use strongly affect how language is acquired, used, and changes over time.” Here we explore the effect of perceptual constraints and social motivation upon the newborn’s increasing autonomy, characterized as “levels of consciousness” The resulting interlocked set of models does *not* try to parametrize the data presented here – the models are exploratory. Nevertheless, the models are constrained by this data. They do suggest how the data might arise, and they are meant to suggest further experiments that will clarify both the data and the models. Because the object here is to concentrate on the effects of social interaction on the acquisition of language, the treatment is within a *complex adaptive systems (cas)* framework, as suggested in the manifesto. That is, we consider models in which multiple agents interact and learn from each other. *Cas* emphasize dynamics, and the agents therein rarely settle down to a static equilibrium. This ongoing dynamic suggests that each agent will develop its own idiolect, while agents interacting regularly will have many common constructions in their idiolects. This, indeed, is a familiar finding of modern linguistics. It is our intention to build executable versions of these models, testing them and extending human experiments in ways that will suggest improvements to the models. Above all, we would like to provide a strong, testable theoretical base for the “levels of consciousness” approach to language acquisition.

References.

Armstrong, D.M. What is Consciousness? In D.M. Armstrong, *The Nature of Mind and Other Essays*. Ithaca, New York: Cornell University Press. 1980.

- Braitenberg, V. *Vehicles: Experiments in Synthetic Psychology*. Cambridge MA: MIT Press. 1984.
- Brooks, P.J., Hanauer, J.B., Padowska, B., & Rosman, H. The role of selective attention in preschoolers' rule use in a novel dimensional card sort. *Cognitive Development*, 117, 1–21. 2003
- Carlson, S.M., & Moses, L.J. Individual differences in inhibitory control and children's theory of mind. *Child Development*, 72, 1032-1053. 2001.
- Carruthers, P. *Language, Thought and Consciousness: an essay in philosophical psychology*. Cambridge: Cambridge University Press. 1996.
- Carruthers, P. *Phenomenal Consciousness: a naturalistic theory*. Cambridge: Cambridge University Press. 2000.
- Chomsky, N. *Aspects of a Theory of Syntax*. Cambridge MA: MIT Press. 1965.
- Craik, F. I. M., & Tulving, E. Depth of processing and the retention of words in episodic memory. *Journal of Experimental Psychology*, 104, 268-294. 1975.
- Ebeling, K., & Gelman, S. Coordination of size standards by young children. *Child Development*, 59, 888-896. 1988.
- Ebeling, K., & Gelman, S. Children's use of context in interpreting “big” and “little.” *Child Development*, 65, 1178-1192. 1994.
- Elder, J.L., & Pederson, D.R. Preschool children's use of objects in symbolic play. *Child Development*, 49, 500–504. 1978.
- Five Graces Group [C. Beckner, R. Blythe, J. Bybee, M. H. Christiansen, W. Croft, N. C. Ellis, J. H. Holland, J. Ke, D. Larsen-Freeman, T. Schoenemann]. *Language Is a Complex Adaptive System*. [to appear].
- Frye, D., Zelazo, P.D., & Palfai, T. Theory of mind and rule-based reasoning. *Cognitive Development*, 10, 483-527. 1995.
- Gao, H. *The physical foundation of the patterning of physical action verbs*. Lund, Sweden: Lund University Press. 2001.
- Gao, H.H., & Zelazo, P.D. Language and development of consciousness: degrees of disembodiment. In W.F. Overton, U. Mueller, & J. Newman (Eds.), *Developmental Perspectives on Embodiment and Consciousness*. pp. 225-246. Mahwah, NJ: Erlbaum. 2008.
- Gao, H.H., Zelazo, P.D., & Debarbara, K. Beyond early linguistic competence: Development of children's ability to interpret adjectives flexibly (paper presented at 2005 Biennial Meeting of Society for Research in Child Development, April 7-10, Atlanta, Georgia, U.S.)

- Hebb, D.O. *The Organization of Behavior*. New York: Wylie. 1949.
- Holland, J.H. *Emergence: From Chaos to Order*. New York: Addison-Wesley. 1998.
- Holland, J.H. *Hidden Order: How Adaptation Builds Complexity*. New York: Addison-Wesley. 1995.
- Holland, J.H., Holyoak, K.J., Nisbett, R.E., & Thagard, P.R. *Induction: Processes of Inference, Learning, and Discovery*. Cambridge MA: MIT Press. 1986.
- Jacques, S., & Zelazo, P.D. Language and the development of cognitive flexibility: Implications for theory of mind. In J.W. Astington, & J.A. Baird (Eds.), *Why Language Matters for Theory of Mind* (pp. 144-162). New York: Oxford University Press. 2005.
- Jacques, S., Zelazo, P.D., Kirkham, N.Z., & Semcesen, T.K. Rule selection and rule execution in preschoolers: An error-detection approach. *Developmental Psychology*, 35, 770-780. 1999.
- Jacques, S., Zelazo, P.D., Lourenco, S.F., & Sutherland, A.E. The roles of labeling and abstraction in the development of cognitive flexibility. [Manuscript under review. 2006].
- James, W. *The Varieties of Religious Experience: A Study in Human Nature*. New York and London: Longmans, Green and Co. 1902.
- Kelly, G.A. *The Psychology of Personal Constructs*. New York: Norton. 1955. Reprinted by Routledge (London), 1991.
- Luria, A.R. *The Role of Speech in the Regulation of Normal and Abnormal Behavior*. New York: Liveright. 1961.
- Marcovitch, S., & Zelazo, P.D. The A-not-B error: Results from a logistic meta-analysis. *Child Development*, 70, 1297-1313. 1999.
- Moscovitch, M. Models of consciousness and memory. In M.S. Gazzaniga (ed.), *The Cognitive Neurosciences*. MIT Press. 1995.
- O'Reilly, A.W. Using representations: Comprehension and production of actions with imagined objects. *Child Development*, 66, 999-1010. 1995.
- Overton, W.F., & Jackson, J.P. The representation of imagined objects in action sequences: A developmental study. *Child Development*, 44, 309-314. 1973.
- Pederson, D.R.; Rook-Green, A., & Elder, J.L. The role of action in the development of pretend play in young children. *Developmental Psychology*, 17, 756-759. 1981.
- Perner, J., & Lang, B. What causes 3-year olds' difficulty on the dimensional change card sorting task? *Infant & Child Development*, 11, 93-105. 2002.

- Perner, J., & Lang, B. Development of theory of mind and executive control. *Trends in Cognitive Sciences*, 3, 337–344. 1999.
- Piaget, J. *Construction of Reality in the Child*. New York: Basic Books. 1954.
- Reedy, G. *Robert South (1634-1716): An Introduction to His Life and Sermons*. Cambridge University Press. 1992.
- Schacter, D.L. On the relation between memory and consciousness. In H.L. Roediger III, & F.I.M. Craik (Eds.), *Varieties of Memory and Consciousness: Essays in honor of Endel Tulving* (pp.355-389). Hillsdale, NJ: Erlbaum Associates. 1989.
- Schooler, J.W./Fiore, S.M. Consciousness and the limits of language: You can't always say what you think or think what you say. In Cohen/Schooler, *Scientific Approaches to Consciousness*, 241—293. 1997.
- Shelley, P.B. *Prometheus Unbound*. Kessinger Publishing ISBN: 1419143239. p.56. [first published in 1820]
- Talleyrand, Charles-Maurice de Talleyrand-Périgord (1754 - 1838). Horay: ISBN 2705803327. 2002.
- Tomasello, M. Do young children have adult syntactic competence? *Cognition*, 74(3), 209-253. 2000.
- Ungerer, J.A., Zelazo, P.R., Kearsley, R.B., & O'Leary, K. Developmental changes in the representation of objects in symbolic play from 18 to 34 months of age. *Child Development*, 52, 186–195. 1981.
- Voltaire, F.M.A. *The Philosophy Of History*. London, I. Allcock. Octavo. viii,316pp. First edition in English. 1766.
- Vygotsky, L.S. *Mind in Society*. Cambridge, MA: MIT Press. 1978.
- Zelazo, P.D., Gao, H. H., & Todd, R. Development of consciousness. In P. D. Zelazo, M. Moscovitch, & E. Thompson (Eds.), *The Cambridge Handbook of Consciousness*. pp. 405-434. New York: Cambridge University Press. 2007.
- Zelazo, P.D. The development of conscious control in childhood. *Trends in Cognitive Sciences*, 8, 12-17. 2004.
- Zelazo, P.D. The dimensional change card sort (DCCS): A method of assessing executive function in children. *Nature Protocols*, 1, 297-301. 2006.