

---

Karmiloff-Smith, A. (1992, reprinted 1995) *Beyond Modularity: A Developmental Perspective on Cognitive Science*. Cambridge, Mass.: MIT Press/Bradford Books.

## Chapter 1

### Taking Development Seriously

---

*Nature has contrived to have it both ways, to get the best out of fast dumb systems and slow contemplative ones, by simply refusing to choose between them. (Fodor 1985, p. 4)*

Have you noticed how quite a large number of developmental psychologists are loath to attribute any innate predispositions to the human infant? Yet they would not hesitate to do so with respect to the ant, the spider, the bee, or the chimpanzee. Why would Nature have endowed every species except the human with some domain-specific predispositions? Yet, if it turns out that all species have such predispositions, that most can maintain a goal in the face of changing environmental conditions, and that most have the capacity for learning on the basis of interaction with conspecifics and the physical environment, what is special about human cognition? Is it simply that the *content* of knowledge differs between species? Is it language that makes humans special? Or are there qualitatively different processes at work in the human mind? Does human cognitive change affect all domains of knowledge simultaneously, or does development occur in a domain-specific fashion? Are cross-species differences relevant only to adult cognition, or do humans differ from other species from birth?

This book sets out to address such questions and to demonstrate that one can attribute various innate predispositions to the human neonate without negating the roles of the physical and sociocultural environments and without jeopardizing the deep-seated conviction that we are special—creative, cognitively flexible, and capable of conscious reflection, novel invention, and occasional inordinate stupidity.

*Is the Initial Architecture of the Infant Mind Modular?*

Fodor's 1983 book *The Modularity of Mind* (which I later criticize) made a significant impact on developmental theorizing by suggesting how

---

the nativist thesis and the domain-specificity of cognition are relevant to constraints on the architecture of the human mind. For Fodor, the notion of "architecture" refers to the organization of relatively fixed and highly constrained innate specifications: the invariant features of the human information-processing system. Unlike Bruner (1974–75) and Piaget (1952b), who argue for domain-general development, Fodor holds that the mind is made up of genetically specified, independently functioning, special-purpose "modules" or input systems.<sup>1</sup> Like Fodor, I shall use the terms "module" and "input system" as synonyms. Each functionally distinct module has its own dedicated processes and proprietary inputs.

According to Fodor, information from the external environment passes first through a system of sensory transducers, which transform the data into formats that each special-purpose input system can process. Each input system, in turn, outputs data in a common format suitable for central, domain-general processing. The modules are deemed to be hard-wired (not assembled from more primitive processes), of fixed neural architecture, domain specific, fast, autonomous, mandatory, automatic, stimulus driven, giving rise to shallow outputs, and insensitive to central cognitive goals.

A further characteristic of modules is that they are informationally encapsulated (or, as Pylyshyn [1980] put it, "cognitively impenetrable"). Other parts of the mind can neither influence nor have access to the internal workings of a module, only to its outputs. Modules have access only to information from stages of processing at lower levels, not to information from top-down processes. In other words, what the mind knows and believes cannot affect the workings of a module.

For Fodor, the essential fact about modules is their informational encapsulation. He is neutral about whether they are resource encapsulated (i.e., whether different modules share, say, inference algorithms<sup>2</sup>). In defense of informational encapsulation, Fodor cites the example of perceptual illusions such as the Muller-Lyer illusion (figure 1.1). In that illusion, even when subjects have measured the

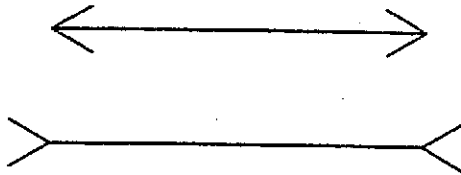


Figure 1.1  
The Muller-Lyer illusion.

two lines and thus have explicit knowledge of their equal length, they cannot prevent themselves from seeing one of the lines as longer than the other, depending on the direction of the arrowheads at their extremities. The subject's explicit knowledge about equal line length, available in what Fodor calls the "central system," is not available to the perceptual system's computation of relative lengths. In other words, the module for perceptual processing is self-contained and has no access to the information elsewhere in the mind. Gallistel (1990) gives a similar definition when discussing the cognitive architecture of other species. For instance, although the rat can represent nongeometric data (such as color, smell, and texture) and can use them for various purposes, the rat's system for determining position and heading in space can make use of geometric data only. It is impenetrable to information from nongeometric sources, even when such data are highly relevant to the rat's current goal.

For Fodor, it is the *co-occurrence* of all the properties discussed above that defines a module or an input system. Alone, particular properties do not necessarily entail modularity. For instance, rapid automatic processing can also take place outside input systems. Anderson (1980) provides examples of this from skill learning.<sup>3</sup> He shows that, when learning a new skill, subjects initially focus consciously on component parts, but that once skill learning is complete the parts become compiled into a procedure which is executed rapidly, automatically, and unconsciously. Such task-specific expertise should not be confounded with the Fodorian concept of a module, which includes hard wiring, fixed neural architecture, mandatory stimulus-driven processing, informational encapsulation, and insensitivity to central cognitive goals.

Each module is like a special-purpose computer with a proprietary database. By "proprietary" Fodor means that a module can process only certain types of data and that it automatically ignores other, potentially competing input. A module computes in a bottom-up fashion a constrained class of specific inputs; that is, it focuses on entities that are relevant to its particular processing capacities only. And it does so whenever relevant data present themselves—that is, an input system cannot refrain from processing. This enhances automaticity and speed of computation by ensuring that the organism is insensitive to many potential classes of information from other input systems and to top-down expectations from central processing.

Input systems, then, are the parts of the human mind that are inflexible and unintelligent. They are the stupidity in the machine—but they are just what a young organism might need to get initial cognition off the ground speedily and efficiently.

I argue that development involves a process of going beyond modularity. For Fodor, however, development doesn't really exist.<sup>4</sup> Rather, Fodor posits a built-in dichotomy between what is computed blindly by the input systems and what the organism "believes." It is in "central processing" that the human belief system is built up, by deriving top-down hypotheses about what the world is like from the interface between the outputs of input systems and what is already stored in long-term memory. In contrast with input systems, Fodor considers central processing to be influenced by what the system already knows, and therefore to be relatively unencapsulated, slow, nonmandatory, controlled, often conscious, and influenced by global cognitive goals. Central processing receives outputs from each input system in a common representational format, a language of thought (Fodor 1976). Central processing, then, is general-purpose. It is devoted to the fixation of belief, the building up of encyclopedic knowledge, and the planning of intelligent action, in contrast to the special-purpose, domain-specific computations of modules.

While endorsing the importance of several aspects of Fodor's thesis for understanding the architecture of the human mind, I shall provide a view that differs from the notion that modules are prespecified in detail, and shall question the strictness of the dichotomy that Fodor draws between modules and central processing.<sup>5</sup> I shall also challenge Fodor's contention that the outputs of input systems are automatically encoded into a single common language of thought.

#### *Prespecified Modules versus a Process of Modularization*

Fodor's detailed account of the encapsulation of modules focuses predominantly on their role in on-line processing. There is little discussion of ontogenetic change, except to allow for the creation of new modules (such as a reading module). Fodor takes it as demonstrated that modules for spoken language and visual perception are innately specified. By contrast, I wish to draw a distinction between the notion of prespecified modules and that of a process of *modularization* (which, I speculate, occurs repeatedly as the *product* of development). Here I differ from Fodor's strict nativist conception. I hypothesize that if the human mind ends up with any modular structure, then, even in the case of language, the mind becomes modularized *as development proceeds*. My position takes account of the plasticity of early brain development (Neville 1991; Johnson, in press). It is plausible that a fairly limited amount of innately specified, domain-specific predispositions (which are not strictly modular) would be sufficient to constrain the classes of inputs that the infant mind computes. It can thus be hy-

pothesized that, *with time*, brain circuits are progressively selected for different domain-specific computations; in certain cases, relatively encapsulated modules would be formed. Thus, when I use the term "innately specified" in this book, I do not mean to imply anything like a genetic blueprint for prespecified modules, present at birth.<sup>6</sup> Rather, as will be clear, I argue for innately specified predispositions that are more epigenetic than Fodor's nativism. The view that I adopt throughout the book is that Nature specifies initial biases or predispositions that channel attention to relevant environmental inputs, which in turn affect subsequent brain development.<sup>7</sup>

The thesis that development involves a process of gradual modularization rather than prespecified modules remains speculation at this point in time. It will not, therefore, be developed further in the book. However, it does merit mention in this introductory chapter to delineate the extent to which I find Fodor's views useful for thinking about the human mind and the extent to which I call for certain modifications. Together with quite a number of cognitive developmentalists, I think Fodor's thesis has pointed to where a domain-general view of development such as Piaget's is likely to be wrong. However, I shall argue for a more dynamic view of development than Fodor's modularity of mind.

The choice between prespecified modules and modularization is an empirical one. Only future research using on-line brain-activation studies with neonates and young infants can distinguish between the two hypotheses. If Fodor's thesis of prespecified modularity is correct, such studies should show that, from the very outset, specific brain circuits are activated in response to domain-specific inputs. By contrast, if the modularization thesis is correct, activation levels should initially be relatively distributed across the brain, and only with time (and this could be a short or relatively long time during infancy) would specific circuits always be activated in response to domain-specific inputs.<sup>8</sup> The modularization thesis allows us to speculate that, although there are maturationally constrained attention biases and domain-specific predispositions that channel the infant's early development, this endowment interacts richly with, and is in return affected by, the environmental input.

Whatever its shortcomings, Fodor's modularity thesis has offered cognitive science much food for thought. Nonetheless, I aim to challenge Fodor's dismissal of the relevance of a developmental perspective on cognitive science. Development, in my view, is the key to understanding the adult mind. Moreover, I question Fodor's oft-cited claim that "the limits of modularity are also likely to be the limits of what we are going to be able to understand about the mind" (1983,

p. 126). I shall argue that cognitive scientists can go beyond modularity to study the more creative aspects of human cognition. But my contention is that such an endeavor will be greatly enhanced by a developmental perspective on the problem.

#### *What Constitutes a Domain?*

Irrespective of whether they agree with Fodor's strict modularity thesis, many psychologists now consider development to be "domain specific." Much depends, of course, on what one understands by "domain," and it is important not to confuse "domain" with "module." From the point of view of the child's mind, a domain is the set of representations sustaining a specific area of knowledge: language, number, physics, and so forth. A module is an information-processing unit that encapsulates that knowledge and the computations on it. Thus, considering development domain specific does not necessarily imply modularity. In other words, the storing and processing of information may be domain specific without being encapsulated, hard-wired, or mandatory.

Fodor's discussion of modularity is defined over very broad domains, such as language. He talks, for instance, of the "language module" and the "perceptual module." Others tend to draw finer distinctions within a domain—e.g., the syntactic module, the semantic module, and the phonological module. Still others (Marslen-Wilson and Tyler 1987) reject the notion of on-line modularity of processing altogether. Throughout the book, I shall argue for domain specificity of development rather than modularity in the strict Fodorian sense. I shall retain the term "domain" to cover language, physics, mathematics, and so forth. I will also distinguish "microdomains" such as gravity within the domain of physics and pronoun acquisition within the domain of language. These microdomains can be thought of as subsets within particular domains.

The need for this finer distinction of what constitutes a domain stems from the fact that I will put forward a *phase* model of development, rather than a *stage* model. In a stage model, such as Piaget's, overarching changes occur more or less simultaneously across different domains. One alternative view is that broad changes occur within a domain—for example, that a particular type of change occurs first with respect to language and later with respect to physics. The model discussed in this book differs from both of these conceptions. It invokes *recurrent phase changes* at different times across different microdomains and repeatedly within each domain. Take the case of the domain of language as an example. In the microdomain of pronoun

acquisition, a sequence of changes X-Y-Z (e.g., from implicit to explicit to verbal justification) might be complete in a child by age 7, whereas in the microdomain of understanding what a word is the same sequence might already be complete by age 5. I shall thus distinguish the broad domains (language, mathematics, and so forth) from the microdomains (e.g. pronouns and counting) that they subsume. Whenever I refer to domain-general or domain-specific theories, these are situated at the level of broad domains.

#### *Development from a Domain-General Perspective*

Fodor's nativist thesis is in sharp contrast with domain-general theories of learning, such as Piaget's constructivist epistemology, which were once popular in the development literature.<sup>9</sup> Piagetian theory argues that neither processing nor storage is domain specific. Of course, implicitly at least, Piagetians must acknowledge that there are different sensory transducers for vision, audition, touch, and so forth. They do not accept, however, that the transducers transform data into innately specified, domain-specific formats for modular processing. For Piagetians, development involves the construction of domain-general changes in representational structures operating over all aspects of the cognitive system in a similar way.

At this juncture I shall risk outraging some of my former colleagues at Geneva University by suggesting that Piaget and behaviorism have much in common. What, link Piaget and Skinner? An aberration, to be sure! Yet I arrive at this *liaison dangereuse* between such unlikely bedfellows by opposing the domain-general view with the domain-specific explanation of development.

Neither the Piagetian nor the behaviorist theory grants the infant any innate structures or domain-specific knowledge. Each grants only some domain-general, biologically specified processes: for the Piagetians, a set of sensory reflexes and three functional processes (assimilation, accommodation, and equilibration); for the behaviorists, inherited physiological sensory systems and a complex set of laws of association. These domain-general learning processes are held to apply across all areas of linguistic and nonlinguistic cognition. Piaget and the behaviorists thus concur on a number of conceptions about the initial state of the infant mind. The behaviorists saw the infant as a *tabula rasa* with no built-in knowledge (Skinner 1953); Piaget's view of the young infant as assailed by "undifferentiated and chaotic" inputs (Piaget 1955a) is substantially the same.

Needless to say, there are fundamental differences between these two schools. Piagetians view the child as an active information con-

structor, behaviorists as a passive information storer. Piagetians conceive of development as involving fundamental stage-like changes in logical structure, whereas behaviorists invoke a progressive accumulation of knowledge. However, in the light of the present state of the art in developmental theorizing, Piagetians and behaviorists have much in common in their view of the neonate's "knowledge-empty" mind and their claims that domain-general learning explains subsequent development across all aspects of language and cognition.

*Development from a Domain-Specific Perspective*

The nativist/modularity thesis projects a very different picture of the young infant. Rather than being assailed by incomprehensible, chaotic data from many competing sources, the neonate is seen as preprogrammed to make sense of specific information sources. Contrary to the Piagetian or the behaviorist infant, the nativist infant is off to a very good start. This doesn't, of course, mean that nothing changes during infancy and beyond; the infant has much to learn. But the nativist/modularity stance posits that subsequent learning is guided by innately specified, domain-specific principles, and that these principles determine the entities on which subsequent learning takes place (Gelman 1990b; Spelke 1991).

The domain specificity of cognitive systems is also suggested by developmental neuropsychology and by the existence of children in whom one or more domains are spared or impaired. For example, autism may involve a single deficit in reasoning about mental states (theory of mind), with the rest of cognition relatively unimpaired. Williams Syndrome, by contrast, presents a very uneven cognitive profile in which language, face recognition, and theory of mind seem relatively spared, whereas number and spatial cognition are severely retarded. And there are numerous cases of idiots-savants in whom only one domain (such as drawing or calendrical calculation) functions at a high level, while capacities are very low over the rest of the cognitive system. By contrast, Down Syndrome is suggestive of a more across-the-board, domain-general deficit in cognitive processing.

Adult brain damage points to domain specificity, also. It is remarkably difficult to find convincing examples in the neuropsychological literature of an across-the-board, domain-general disorder (Marshall 1984), although a case might be made for an overall deficit in planning in patients with prefrontal damage (Shallice 1988). But in many instances, disorders of higher cognitive functions consequent upon brain damage are typically domain specific—that is, they affect only



face recognition, number, language, or some other facility, leaving the other systems relatively intact.

So if adults manifest domain-specific damage, and if it can be shown that infants come into the world with some domain-specific predispositions, doesn't that mean that the nativists have won the debate over the developmentalists still ensconced on the theoretical shores of Lake Geneva (Piaget's former bastion of anti-nativism and anti-modularity)? Not necessarily, because it is important to bear in mind that the greater the amount of domain-specific properties of the infant mind, the less creative and flexible the subsequent system will be (Chomsky 1988). Whereas the fixed constraints provide an initial adaptive advantage, there is a tradeoff between the efficiency and automaticity of the infant's input systems, on the one hand, and their relative inflexibility, on the other. This leads me to a crucial point: *The more complex the picture we ultimately build of the innate capacities of the infant mind, the more important it becomes for us to explain the flexibility of subsequent cognitive development.* It is toward such an end—exploring the flexibility and creativity of the human mind beyond the initial state—that my work in language acquisition and cognitive development has been concentrated, in an attempt to determine both the domain-specific and the domain-general contributions to development. It is implausible that development will turn out to be entirely domain specific or domain general. And although I will need to invoke some built-in constraints, development clearly involves a more dynamic process of interaction between mind and environment than the strict nativist stance presupposes.

#### *Reconciling Nativism and Piaget's Constructivism*

What theory of development could encompass the dynamics of a rich process of interaction between mind and environment? At first blush, a theory with a central focus on epigenesis and constructivism, like Piaget's, would seem the most appropriate. The notion of constructivism in Piaget's theory<sup>10</sup> is the equivalent at the cognitive level of the notion of epigenesis at the level of gene expression. For Piaget both gene expression and cognitive development are emergent products of a self-organizing system that is directly affected by its interaction with the environment. This general aspect of Piaget's theory, if more formalized, may well turn out to be appropriate for future explorations of the notion of progressive modularization discussed above. However, much of the rest of Piaget's theory has come under a great deal of criticism. A growing number of cognitive developmentalists<sup>11</sup> have become disenchanted with Piaget's account of the infant as a purely

sensorimotor organism. For Piaget the newborn has no domain-specific knowledge, merely sensory reflexes and the three domain-general processes of assimilation, accommodation, and equilibration. By contrast, the infancy research that I shall discuss in the following chapters suggests that there is considerably more to the initial functional architecture of the brain than Piaget's theory posits. Yet the exclusive focus of nativists like Fodor and Chomsky on biologically specified modules leaves little room for rich epigenetic-constructivist processes. Moreover, Fodor's concentration on input systems—he has far less to say about either output systems or central processing—doesn't help us to understand the way in which children turn out to be active participants in the construction of their own knowledge.

Although for Chomsky (1988) and Spelke (1991) a nativist stance precludes constructivism, I argue that nativism and Piaget's epigenetic constructivism are not necessarily incompatible—with certain provisos. First, to Piaget's view one must add some innate, knowledge-impregnated predispositions<sup>12</sup> that would give the epigenetic process a head start in each domain. This does not imply merely adding a little more domain-general structure than Piaget supposed. Rather, it means adding domain-specific biases to the initial endowment. But the second proviso for the marriage of constructivism and nativism is that the initial base involve less detailed specifications than some nativists presuppose and a more progressive process of *modularization* (as opposed to prespecified modules). Fodor does not, for instance, discuss the cases in which one of his prespecified modules cannot receive its proprietary input (e.g., auditory input to a language module in the case of the congenitally deaf). We know that in such cases the brain selectively adapts to receive other (e.g., visuomanual) nonauditory inputs, which it processes linguistically (Changeux 1985; Neville 1991; Poizner et al. 1987). Many cases of early brain damage indicate that there is far more plasticity in the brain than Fodor's strict modularity view would imply. The brain is not prestructured with ready-made representations; it is channeled to progressively *develop* representations via interaction with both the external environment and its own internal environment. And, as I stressed above, it is important not to equate innateness with presence at birth or with the notion of a static genetic blueprint for maturation. Whatever innate component we invoke, it becomes part of our biological potential only through interaction with the environment; it is latent until it receives input (Johnson 1988; Johnson, in press; Marler 1991; Oyama 1985; Thelen 1989). And that input affects development in return.

The proposed reconciliation of nativism and constructivism will allow us to adhere to Piaget's epigenetic-constructivist view of the

developmental process, but to drop his insistence on domain generality in favor of a more domain-specific approach. Furthermore, the Piagetian focus on output systems (i.e., on the infant's and the child's *action on the environment*) is an important addition to the nativist's accent on input systems. But Piaget's strong anti-nativism and his arguments for across-the-board stages no longer constitute a viable developmental framework.<sup>13</sup>

The need to invoke domain specificity will be apparent throughout the book. For example, it will become clear in chapter 2 that domain-general sensorimotor development alone cannot explain the acquisition of language. Syntax does not simply derive from exploratory problem solving with toys, as some Piagetians claim. Lining up objects does not form the basis for word order. Trying to fit one toy inside another has nothing to do with embedded clauses. General sensorimotor activity alone cannot account for specifically linguistic constraints; if it could, then it would be difficult to see why chimpanzees, which manifest rich sensorimotor and representational abilities, do not acquire anything remotely resembling human language despite extensive training (Premack 1986).<sup>14</sup>

Despite these criticisms of Piaget's view of early infancy and my rejection of his stage view of development, I hope by the end of the book to have persuaded you that important aspects of Piaget's epistemology should be salvaged and that there is far more to cognitive development than the unfolding of a genetically specified program. If we are to understand the human mind, our focus must stretch well beyond the innate specifications. Infants and young children are active constructors of their own cognition. This involves both domain-specific constraints and domain-general processes.

In sum, there seems to be something right about both Fodor's and Piaget's approaches to human cognition. My own solution to this potential dilemma has been to take an epistemological stance that encompasses aspects of both nativism and constructivism.

### *The Notion of Constraints on Development*

Nowadays, many discussions in developmental psychology concern constraints on development.<sup>14</sup> But domain-general and domain-specific theories treat the notion of constraints differently. For the domain-general theorist, the word "constraints" carries a negative connotation; it is taken as referring to factors which curtail a child's competence. By contrast, for the domain-specific theorist "constraints" takes on a positive connotation: Domain-specific constraints *potentiate* learning by limiting the hypothesis space entertained. They enable the infant

to accept as input only those data which it is initially able to compute in specific ways. The domain specificity of processing provides the infant with a limited yet organized (nonchaotic) system from the outset, and not solely at the tail end of the Piagetian sensorimotor period.<sup>15</sup>

### *New Paradigms for Studying Young Infants*

Piaget's pioneering experimental work on development was focused on older children. For his exploration of infancy, Piaget had to rely solely on observation of his own three children. There were no paradigms available then for the experimental study of early infancy. Since the mid 1960s, however, methodological innovations have opened up exciting new experimental possibilities. Experiments now focus on the different input systems through which newborns and young infants compute data relevant to a variety of cognitive domains. And, although I do not share Fodor's pessimism that we shall never understand central systems,<sup>16</sup> he is right that input systems are much more amenable to strict experimental research, particularly in infancy.

Let me digress for a moment to look briefly at the new paradigms for infancy research, since they will crop up throughout the book. These paradigms have been used by researchers interested in the infant's sensitivity to data relevant to language, physics, number, human intention, two-dimensional notation, and so forth. They are thus important for all the chapters in this book.

The new experimental approaches were devised to surmount problems arising from Piagetian-inspired research which required infants to demonstrate their abilities by manual search. Neonates and young infants cannot engage in manual search. What they do well is suck and look (and, alas for parents, cry). These capacities form the basis of the new methodologies. There are three main infancy techniques; two fall under the habituation/dishabituation paradigm, and the third uses preferential looking or listening.

In the habituation/dishabituation paradigm, the infant is presented repeatedly with the same stimulus set until it shows lack of interest by starting to attend for shorter times. Then a different stimulus set is presented. If the infant shows renewed interest by attending for a longer time, it can be concluded that the new stimulus is apprehended (perceived, understood) by the infant as different from the earlier one. The stimulus set can be visual, auditory, or tactile, depending on the experiment. An infant's interest in an event (e.g., seeing a circle after a series of squares of different sizes and colors) typically manifests itself as prolonged attention. By clever manipulation of variables of

shape, color, size, and so forth, the researcher can home in on the nature of the difference to which the infant is sensitive. Say the newborn shows decreasing interest in squares despite constant variations in size and color, but suddenly shows renewed interest on the first presentation of a circle; then one can conclude that shape discrimination is present at birth and does not have to be learned. By contrast, if the newborn continues to show lack of interest on presentation of the circle, one can conclude that the circle is apprehended as being equivalent to the set of squares—i.e., that shape discrimination is a later achievement (although in fact, as Slater [1990] has shown, it is present at birth). The same logic is used to test discriminations of other types of stimuli.

"Interest" is measured either by greater amplitude of sucking or by longer length of looking. In the former case, the infant is given a non-nutritive pacifier which is attached to an apparatus that measures sucking amplitude. As the infant habituates to the original stimulus, its sucking amplitude decreases. If the new stimulus is apprehended as different, the infant's sucking amplitude increases; if not, it plateaus or decreases further. As will be discussed in chapter 2, such a technique has been used to explore the infant's preference for listening to its mother tongue over other linguistic input, as well as its capacity for categorical perception of various speech sounds. Thus, if the infant is presented with a set of "va" sounds, and then after habituation with a set of "ba" sounds, increased sucking amplitude demonstrates the infant's sensitivity to the difference between the sounds (i.e., to voice-onset time). Such techniques help us to explore the effects of environmental input on innate predispositions. For a child in a Spanish-speaking environment, for instance, sensitivity to the distinction between "va" and "ba" may be present early in infancy but disappear once the patterns of the input language have been learned, because spoken Spanish does not differentiate between "va" and "ba".

The technique for measuring looking time is based on the same principle as the one measuring sucking amplitude. The infant is repeatedly exposed to a visual stimulus. Each time the stimulus is presented, the infant will look at it for a shorter length of time, until it habituates. After habituation to a given stimulus set, the infant's length of looking at a new stimulus is recorded as a measure of its renewed interest or its boredom. Again, subtle manipulation of variables can determine the features to which the infant is particularly sensitive. The use of this technique will be discussed in chapter 3. For example, infants show surprise (look longer) at a display of a ball that seems to stop in mid-air without support, or at a display of an object

that appears to have passed through a solid surface—that is, they are sensitive to violations of certain laws of physics.

Measuring looking time is somewhat more subjective than measuring sucking amplitude. Thus, looking time must be recorded by observers unaware of the particular display being viewed by the infant on any trial. But, as Spelke (1985) has pointed out,<sup>17</sup> the interpretation of test-trial looking and sucking patterns in experiments of this kind depends on the finding, now obtained in hundreds of laboratories throughout the world, that habituation to one stimulus set is followed by longer looking (or longer sucking) for the test display. In other words, the interpretation rests on the fact that infants extract a common feature across the set of stimuli in the habituation display, and differentiate that from a specific feature of the test display.

A third infancy paradigm involves preferential looking or listening. Here habituation and dishabituation are not measured; rather, the infant is presented with two stimulus displays simultaneously and measurement is taken of which display the infant prefers to look at. Again, measurements are determined by observers who cannot see the displays visible to the infant. Chapter 4 illustrates uses of this technique to measure infants' capacity to match the number of auditory stimuli (e.g., three drumbeats) to the number of objects in either of two visual displays, one containing two objects and the other containing three.

Although the infancy data discussed throughout the book are truly impressive, certain questions about the habituation and preferential techniques remain open. Does the violation of a physical principle have to be extreme, or are infants just as sensitive to subtler violations? What conclusions can legitimately be drawn from the demonstration that the infant is sensitive to a novel stimulus: that domain-specific attention biases and principles are built into the infant mind, or merely that we have trained infants to discriminate in the course of the actual experiment? Any particular experiment would remain inconclusive on this issue. However, if results from different experiments demonstrate that newborns or 4-month-olds can make discriminations for one set of stimuli but cannot do so for another, then it cannot be claimed that discrimination is solely the result of task-specific learning. Rather, discrimination is constrained by whether or not the infant can already show sensitivity to the particular characteristics of the stimuli. This allows tentative conclusions regarding innate specifications and those involved in subsequent learning—tentative since many other interpretations are possible.

I discuss the infancy research in some detail in the first part of each of chapters 2 through 6. But every time, I go on to show that devel-

opment comprises much more than the domain-specific constraints. In particular, it involves "representational redescription," a process that increases the flexibility of the knowledge stored in the mind.

*Beyond Domain-Specific Constraints: The Process of Representational Redescription*

How does information get stored in the child's mind? I argue that there are several different ways. One is via innate specification as the result of evolutionary processes. Innately specified predispositions can either be specific or nonspecific (Johnson and Bolhuis 1991). In both cases, environmental input is necessary. When the innate component is specified in detail, it is likely that the environment acts simply as a trigger for the organism to select one parameter or circuit over others. (Changeux 1985; Chomsky 1981; Piatelli-Palmerini 1989).<sup>18</sup> By contrast, when the innate predisposition is specified merely as a bias or a skeletal outline, then it is likely that the environment acts as much more than a trigger—that it actually influences the subsequent structure of the brain via a rich epigenetic interaction between the mind and the physical/sociocultural environment. The skeletal outline involves attention biases toward particular inputs and a certain number of principled predispositions constraining the computation of those inputs. Note that I am hypothesizing that the human mind has *both* a certain amount of detailed specification and some very skeletal domain-specific predispositions, depending on the domain.

There are several other ways in which new information gets stored in the child's mind. One is when the child fails to reach a goal and has to take into account information from the physical environment. Another is generated by the child's having to represent information provided directly by a linguistic statement from, say, an adult. These are both external sources of change.<sup>19</sup> An internal source of change is illustrated by the above-mentioned process of modularization in such a way that input and output processing becomes less influenced by other processes in the brain. This causes knowledge to become more encapsulated and less accessible to other systems. But another essential facet of cognitive change goes in the opposite direction, with knowledge becoming progressively more accessible.

My claim is that a specifically human way to gain knowledge is for the mind to exploit internally the information that it has already stored (both innate and acquired), by redescribing its representations or, more precisely, by iteratively re-representing in different representational formats what its internal representations represent. I will deal with this in detail in a moment.

Finally, there is a form of knowledge change that is more obviously restricted to the human species: explicit theory change, which involves conscious construction and exploration of analogies, thought experiments and real experiments, typical of older children and adults (Carey 1985; Klahr 1992; Kuhn et al. 1988). But I will argue that this more obvious characteristic of human cognition is possible only on the basis of prior representational redescription, which turns *implicit* information into *explicit* knowledge.

To convey a more tangible feel for the theoretical discussion on which I am about to embark, let me start with a couple of examples—one having to do with learning to play the piano and one having to do with learning to solve Rubik's Cube.<sup>20</sup>

When one is learning to play the piano, initially there is a period during which a sequence of separate notes is laboriously practiced. This is followed by a period during which chunks of several notes are played together as blocks, until finally the whole piece can be played more or less automatically.<sup>21</sup> It is something like this that I shall subsequently call "reaching behavioral mastery." But the automaticity is constrained by the fact that the learner can neither start in the middle of the piece nor play variations on a theme (Hermelin and O'Connor 1989). The performance is generated by procedural representations which are simply run off in their entirety. There is little flexibility. At best the learner starts to be able to play the *whole piece* softer, louder, slower, or faster. It is only later that one can interrupt the piece and start at, say, the third bar without having to go back to the beginning and repeat the entire procedure from the outset. I hypothesize that this cannot be done on the basis of the automatized procedural representations. Rather, I posit, it involves a process of representational redescription such that the knowledge of the different notes and chords (rather than simply their run-off sequence) becomes available as manipulable data. It is only after a period of behavioral mastery that the pianist can generate variations on a theme, change sequential order of bars, introduce insertions from other pieces, and so forth. This differentiates, for instance, jazz improvisation from strict adherence to sheet music. The end result is representational flexibility and control, which allows for creativity. Also important is the fact that the earlier proceduralized capacity is not lost: for certain goals, the pianist can call on the automatic skill; for others, he or she calls on the more explicit representations that allow for flexibility and creativity. (Of course, the playing of some pianists remains at the procedural level.)

In contrast with the beginning pianist's initial conscious attention to particular notes, which gradually becomes proceduralized, I found that I had to "switch off" my consciousness to solve Rubik's Cube. In



other words, I had to stop trying to analyze what I was doing until I could actually do it! In the early course of learning to solve the problem, I developed a sort of proprioceptive solution which I could perform very rapidly but which I had much more difficulty repeating at a slower pace. My "knowledge" at that stage was embedded in the procedural representations sustaining the rapid execution. But I did not stop there. After reiterating a solution many times, I found that I started to recognize certain states of the cube and then knew whether or not I was on the path to my solution. But I still could not interrupt my solution and proceed from just any starting state. With more time still, I found that I could predict what the next few moves would be before actually executing them. Finally I came to a point where I could explain the solution to my daughter. She, however, did not use my explicit instructions but went through the same progression from procedural to explicit knowledge that I had experienced (only faster). This movement from implicit information embedded in an efficient problem-solving procedure, to rendering the knowledge progressively more explicit, is a theme that will recur throughout the book. This is precisely what I think development is about: Children are not satisfied with success in learning to talk or to solve problems; they want to understand how they do these things. And in seeking such understanding, they become little theorists.

Development and learning, then, seem to take two complementary directions. On the one hand, they involve the gradual process of proceduralization (that is, rendering behavior more automatic and less accessible). On the other hand, they involve a process of "explicitation" and increasing accessibility (that is, representing explicitly information that is implicit in the procedural representations sustaining the structure of behavior). Both are relevant to cognitive change, but the main focus of this book will be the process of representational explicitation—which, I posit, occurs in a variety of linguistic and cognitive domains throughout development.

### *The RR Model*

For a number of years I have been building a model that incorporates a reiterative process of *representational redescription*. I call this the RR model. I will first make some general points and then provide a summary of the model.

The RR model attempts to account for the way in which children's representations become progressively more manipulable and flexible, for the emergence of conscious access to knowledge, and for children's theory building. It involves a cyclical process by which information

already present in the organism's independently functioning, special-purpose representations is made progressively available, via redescriptive processes, to other parts of the cognitive system. In other words, representational redescription is a process by which implicit information *in* the mind subsequently becomes explicit knowledge *to* the mind, first within a domain and then sometimes across domains.

The process of representational redescription is posited to occur spontaneously as part of an internal drive toward the creation of intra-domain and inter-domain relationships. Although I shall stress the endogenous nature of representational redescription, clearly the process may at times also be triggered by external influences.

The actual *process* of representational redescription is domain general, but it is affected by the form and the level of explicitness of the representations supporting particular domain-specific knowledge at a given time. When I state that representational redescription is domain general, I do not mean to imply that it involves a simultaneous change across domains. Rather, I mean that, within each domain, the process of representational redescription is the same. To reiterate: the RR model is a *phase* model, as opposed to a *stage* model. Stage models such as Piaget's are age-related and involve fundamental changes across the entire cognitive system. Representational redescription, by contrast, is hypothesized to occur recurrently within microdomains throughout development, as well as in adulthood for some kinds of new learning.

I will deal with the RR model and the process of representational redescription again in chapters 7 and 8. But it is essential to outline the model here in order to situate theoretically the empirical research in the following chapters on children as linguists, physicists, mathematicians, psychologists, and notators. At this stage the account may seem rather abstract, but hang in there. I promise that it will become more tangible once I deal with the specific domains in chapters 2 through 6. I also hope that the piano and Rubik's cube analogies will help sustain the discussion.

Let us now look at the RR model in a little detail. Development, I argue, involves three *recurrent* phases. During the first phase the child focuses predominantly on information from the external environment. This initial learning is data driven. During phase 1, for any microdomain, the child focuses on external data to create "representational adjunctions." Representational adjunctions, I hypothesize, neither alter existing stable representations nor are brought into relation with them. Once new representations are stable, they are simply added, domain specifically, to the existing stock, with minimal effect on what is already stored. In other words, independently stored representa-

tional adjunctions do not yet entail what I mean by representational change. Phase 1 culminates in consistently successful performance on whatever microdomain has reached that level. This is what I term "behavioral mastery."

Behavioral mastery does not necessarily imply that the underlying representations are like the adult's. Successful performance can be generated by a sequence of independently stored representations that will ultimately have to be linked into a more coherent system. The same performance (say, correctly producing a particular linguistic form, or managing to balance blocks on a narrow support) can be generated at various ages by very different representations. Later (phase-3) behavior may appear identical to phase-1 behavior. We thus need to draw a distinction, as illustrated in figure 1.2, between *behavioral change* (which sometimes gives rise to a U-shaped developmental curve) and *representational change*, because behavioral mastery is not tantamount to the end point of the developmental progression in a given microdomain.

Phase 1 is followed by an internally driven phase during which the child no longer focuses on the external data. Rather, system-internal dynamics take over such that internal representations become the focus of change. In phase 2, the current state of the child's representations of knowledge in a microdomain predominates over information from the incoming data. The temporary disregard for features of the external environment during phase 2 can lead to new errors and

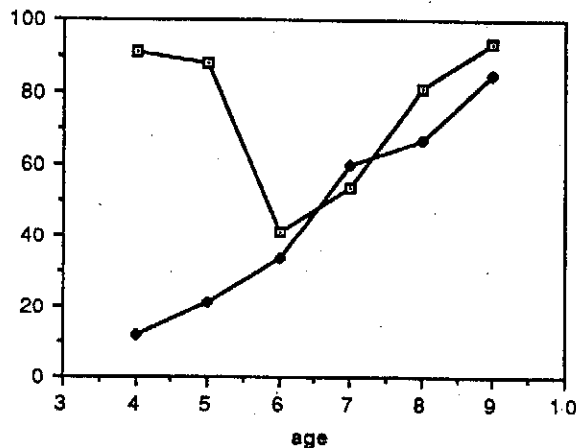


Figure 1.2  
Behavioral change (□) versus representational change (◆).

inflexibilities. This can, but does not necessarily, give rise to a decrease in successful behavior—a U-shaped developmental curve. As figure 1.2 shows, however, this is deterioration at the behavioral level, not at the representational level.

Finally, during phase 3, internal representations and external data are reconciled, and a balance is achieved between the quests for internal and external control. In the case of language, for example, a new mapping is made between input and output representations in order to restore correct usage.

But what about the format of the internal representations that sustain these reiterated phases? The RR model argues for at least four levels at which knowledge is represented and re-represented. I have termed them Implicit (I), Explicit-1 (E1), Explicit-2 (E2), and Explicit-3 (E3). These different forms of representation do not constitute age-related stages of developmental change. Rather, they are parts of a reiterative cycle that occurs again and again within different micro-domains and throughout the developmental span.

The RR model postulates different representational formats at different levels. At level I, representations are in the form of procedures for analyzing and responding to stimuli in the external environment. A number of constraints operate on the representational adjunctions that are formed at this level:

Information is encoded in procedural form.

The procedure-like encodings are sequentially specified.

New representations are independently stored.

Level-I representations are bracketed, and hence no intra-domain or inter-domain representational links can yet be formed.

Information embedded in level-I representations is therefore not available to other operators in the cognitive system. Thus, if two procedures contain identical information, this potential inter-representational commonality is not yet represented in the child's mind. A procedure *as a whole* is available as data to other operators; however, its *component parts* are not. It takes developmental time and representational redescription (see discussion of level E1 below) for component parts to become accessible to potential intra-domain links, a process which ultimately leads (see discussion of levels E2 and E3) to inter-representational flexibility and creative problem-solving capacities. But at this first level, the potential representational links and the information embedded in procedures remain implicit. This gives rise to the ability to compute specific inputs in preferential ways and to respond rapidly

and effectively to the environment. But the behavior generated from level-I representations is relatively inflexible.

The RR model posits a subsequent reiterative process of representational redescription.<sup>22</sup> This involves levels E1, E2, and E3. Level-E1 representations are the results of redescription, into a new compressed format, of the procedurally encoded representations at level I. The redescriptions are abstractions in a higher-level language, and unlike level-I representations they are not bracketed (that is, the component parts are open to potential intra-domain and inter-domain representational links).

The E1 representations are reduced descriptions that lose many of the details of the procedurally encoded information. As a nice example of what I have in mind here, consider the details of the grated image delivered to the perceptual system of a person who sees a zebra (Mandler, in press). A redescription of this into "striped animal" (either linguistic or image-like) has lost many of the perceptual details. I would add that the redescription allows the *cognitive* system to understand the analogy between an actual zebra and the road sign for a zebra crossing (a European crosswalk with broad, regular, black and yellow stripes), although the zebra and the road sign deliver very different inputs to the *perceptual* system. A species without representational redescriptions would not make the analogy between the zebra and the "zebra crossing" sign. The redescribed representation is, on the one hand, simpler and less special purpose but, on the other, more cognitively flexible (because it is transportable to other goals). Unlike perceptual representations, conceptual redescriptions are productive; they make possible the invention of new terms (e.g. "zebrin," the antibody which stains certain classes of cells in striped patterns).

Note that the original level-I representations remain intact in the child's mind and can continue to be called for particular cognitive goals which require speed and automaticity. The redescribed representations are used for other goals where explicit knowledge is required.

Although the process of representational redescription can occur on line, I posit that it also takes place without ongoing analysis of incoming data or production of output. Thus, change may occur outside normal input/output relations, i.e. simply as the product of system-internal dynamics, when there are no external pressures of any kind. I will come back to this point in a moment.

As representations are redescribed into the E1 format, we witness the beginnings of a flexible cognitive system upon which the child's nascent theories can subsequently be built. Level E1 involves explicitly defined representations that can be manipulated and related to other

redescribed representations. Level-E1 representations thus go beyond the constraints imposed at level I, where procedural-like representations are simply used in response to external stimuli. Once knowledge previously embedded in procedures is explicitly defined, the potential relationships between procedural components can then be marked and represented internally. I examine several examples of this below, particularly in chapters 2 and 3. Moreover, once redescription has taken place and explicit representations become manipulable, the child can then introduce violations to her data-driven, veridical descriptions of the world—violations which allow for pretend play, false belief, and the use of counterfactuals. This I explore in detail in chapter 5.

It is important to stress that although E1 representations are available as data to the system, they are not necessarily available to conscious access and verbal report. Throughout the book we shall examine examples of the formation of explicit representations which are not yet accessible to conscious reflection and verbal report, but which are clearly beyond the procedural level. In general, developmentalists have not distinguished between implicitly stored knowledge and E1 representations in which knowledge is explicitly represented but is not yet consciously accessible. Rather, they have drawn a dichotomy between an undefined notion of something implicit in behavior (as if information were not represented in any form) and consciously accessible knowledge that can be stated in verbal form. The RR model postulates that the human representational system is far more complex than a mere dichotomy would suggest. I argue that there are more than two kinds of representation. Levels exist between implicitly stored procedural information and verbally storable declarative knowledge. It is particularly via a developmental perspective that one can pinpoint this multiplicity of levels of representational formats.

The RR model posits that only at levels beyond E1 are conscious access and verbal report possible. At level E2, it is hypothesized, representations are available to conscious access but not to verbal report (which is possible only at level E3). Although for some theorists consciousness is reduced to verbal reportability, the RR model claims that E2 representations are accessible to consciousness but that they are in a similar representational code as the E1 representations of which they are redescrptions. Thus, for example, E1 spatial representations are recoded into consciously accessible E2 *spatial* representations. We often draw diagrams of problems we cannot verbalize. The end result of these various redescrptions is the existence in the mind of multiple representations of similar knowledge at different levels of detail and explicitness.

At level E3, knowledge is recoded into a cross-system code. This common format is hypothesized to be close enough to natural language for easy translation into storable, communicable form. It is possible that some knowledge learned directly in linguistic form is immediately stored at level E3.<sup>23</sup> Children learn a lot from verbal interaction with others. However, knowledge may be stored in linguistic code but not yet be linked to similar knowledge stored in other codes. Often linguistic knowledge (e.g., a mathematical principle governing subtraction) does not constrain nonlinguistic knowledge (e.g., an algorithm used for actually doing subtraction<sup>24</sup>) until both have been redescribed into a similar format so that inter-representational constraints can operate.

In the following chapters, I distinguish three levels of representational format: I, E1, and E2/3. For the present purposes, I do not distinguish between levels E2 and E3, both of which involve conscious access. No research has thus far been directly focused on the E2 level (conscious access without verbal report); most if not all metacognitive studies focus on verbal report (i.e., level E3). However, as mentioned above, I do not wish to foreclose the possibility of consciously accessible spatial, kinesthetic, and other non-linguistically-encoded representations.

There are thus multiple levels at which the same knowledge is re-represented. This notion of multiple encoding is important; development does *not* seem to be a drive for economy. The mind may indeed turn out to be a very redundant store of knowledge and processes.

Before I conclude my account of the RR model, it is important to draw a distinction between the *process* of representational redescription and the ways in which it might be realized in a *model*. The process involves recoding information that is stored in one representational format or code into a different one. Thus, a spatial representation might be recoded into linguistic format, or a proprioceptive representation into spatial format. Each redescription, or re-representation, is a more condensed or compressed version of the previous level. We have just seen that the RR model postulates at least four hierarchically organized levels at which the process of representational redescription occurs. Now, empirical data might refute the existence of this hierarchy (i.e., refute the RR *model*) while leaving the *process* of representational redescription unchallenged. Indeed, as figure 1.3 illustrates, there are several alternative models in which the process of representational redescription might be realized. First, as the RR model presumes, it could involve the passage from implicit representations to a level of explicitly defined representations which are not available to conscious access (level E1), and finally to a format which is available

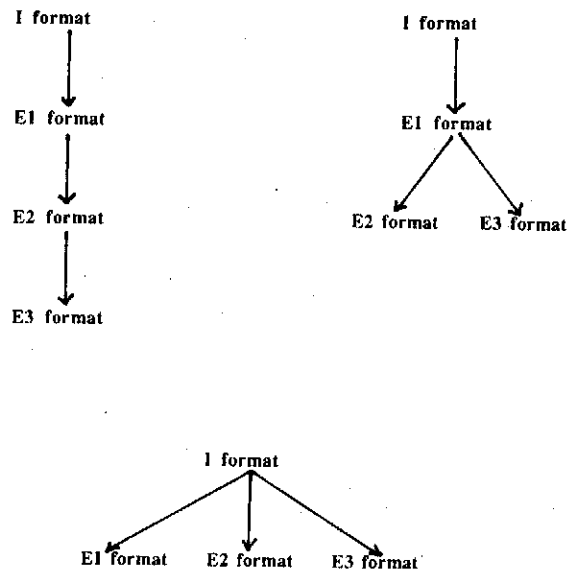


Figure 1.3  
Alternative models of RR.

to conscious access (level E2) and verbal report (level E3). An alternative view would be that implicit representations are redescribed directly into either the E1, the E2, or the E3 format. Thus, information might be directly recoded into linguistic form, rather than via the E1 level (as the RR model posits).

Models can also differ with respect to constraints on the process of representational redescription. For example, a model might postulate that redescription into one or two different formats occurs automatically every time new input is computed and stored. By contrast, the RR model posits that in most instances a period of behavioral mastery must be reached before redescription occurs. Again, if it were shown that redescription occurs before behavioral mastery, the model would require modification but the general concept of the process of representational redescription would remain. The RR model argues for three recurrent phases leading to behavioral mastery and beyond. Again, were it shown that such phases did not exist, the process of redescription would not necessarily be refuted. On the other hand, if the process of representational redescription were to lose its plausibility (i.e., if all representations in the mind were of equivalent status, or if totally distinct constraints were operative on procedural versus



declarative knowledge, rather than each level involving redescription of the previous one), then clearly the model would lose plausibility, too.

Let me again stress the concept of reiterative developmental phases. At any given time the child may have only level-I representations available in one microdomain, but may have E1 representations available in another microdomain and E2/3 representations in yet another. This obviously holds across domains, too. It is hypothesized that there are no overarching domain-general changes in representational format at any given age. There is no such thing as a "phase E2 child". The child's representations are in E2 format with respect to a given microdomain.

The actual *process* of representational redescription is considered domain general, but it operates within each specific domain at different moments and is constrained by the contents and level of explicitness of representations in each microdomain. Again, were each level of representational redescription to turn out to occur across the board at identical ages (e.g., level I up to age 2, level E1 from age 2 to age 4, and E2/3 from age 5 on), which I deem most unlikely, then the model would be refuted and the process would have a different theoretical status.

The model also posits that representational change *within* phases involves adding representational adjunctions. Here negative feedback (failure, incompleteness, inadequacy, mismatch between input and output, etc.) plays an important role, leading progressively to behavioral mastery.<sup>25</sup> But in the transition *between* phases, it is hypothesized that *positive* feedback is essential to the onset of representational redescription. In other words, it is representations that have reached a stable state (the child having reached behavioral mastery) that are redescribed.

This success-based view of cognitive change contrasts with Piaget's view. For Piaget, a system in a state of stability would not spontaneously improve itself. Rather, the Piagetian process of equilibration takes place when the system is in a state of disequilibrium. The RR model also runs counter to the behaviorist view that change occurs as the result of failure or external reinforcement. Rather, for the RR model certain types of change take place *after* the child is successful (i.e., already producing the correct linguistic output, or already having consistently reached a problem-solving goal). Representational redescription is a process of "appropriating" stable states to extract the information they contain, which can then be used more flexibly for other purposes.

I do not, of course, deny the role of cognitive conflict in generating other types of change (through, for instance, the mismatch between theory-driven expectations and actual outcomes). What I am stressing here is the additional—and, I hypothesize, crucial—role of internal system stability as the basis for generating representational redescription. And it is from the repeated process of representational redescription, rather than simply from interaction with the external environment, that cognitive flexibility and consciousness ultimately emerge.

*The Importance of a Developmental Perspective on Cognitive Science*

If our focus is on cognitive flexibility and conscious access to knowledge, why not explore the data from adult psychology? Surely adults are far more cognitively flexible than children, so what justifies a developmental perspective? Not, rest assured, the fact that data from children are cute. One only has to glance at the developmental literature to notice that a sizable number of researchers are absorbed with the ages at which children reach cognitive milestones. But others—and I count myself among them—use the study of development as a theoretical tool for exploring the human mind from a cognitive science perspective. We are not really interested in children *per se*.<sup>26</sup>

A developmental perspective is essential to the analysis of human cognition, because understanding the built-in architecture of the human mind, the constraints on learning, and *how knowledge changes progressively over time* can provide subtle clues to its final representational format in the adult mind. The work of Spelke (1990), which I discuss in chapter 3, has been particularly influential in pointing to the importance of a developmental perspective on cognitive science.<sup>27</sup> For example, the processes for segmenting visual arrays into objects are overlaid, in adults, by other processes for recognizing object categories. But by focusing on how very young infants segment visual arrays into objects before they are able to categorize certain object kinds, Spelke is able to generate new hypotheses about how the adult visual system may function.<sup>28</sup>

Furthermore, distinctions such as declarative/procedural, conscious/unconscious, and controlled/automatic, which are often used to explain adult processing, turn out to involve far more than a dichotomy when explored within a developmental context. But in assuming a developmental perspective we must take the notion “developmental” seriously. Paradoxically, studies on neonates and infants are often not developmental at all. Like studies on adults, they frequently focus not on change but on real-time processing within

steady-state systems. It is of course essential to determine the initial state of the human mind—and for certain abilities the initial state is not necessarily present at birth but is present only after the necessary neurological structures have reached maturation (Mehler and Fox 1985). The notion “developmental” goes beyond the specification of the initial state, however. And a developmental perspective does not apply merely to the details of on-line, steady-state processing in children. Also, it does not simply mean a focus on learning in children of different ages rather than the adult. When making theoretical use of development within a cognitive science perspective, the specific age at which children can successfully perform a task is, to some extent, irrelevant.

The fundamental implication of a developmental perspective involves behavioral and representational change *over time*. I shall often use a later phase in a developmental sequence to understand the status of representations underlying earlier behavior—particularly in the interesting cases where child and adult behaviors are practically identical. This notion of *representational change over time* will be my focus throughout this book. It is for all these reasons that I maintain that a developmental perspective has much to offer cognitive science’s efforts to more fully understand the adult mind.

#### *The Importance of a Cognitive Science Perspective on Development*

Cognitive science focuses on cognition as a form of computation, and on the mind as a complex system that receives, stores, transforms, retrieves, and transmits information. To do so it uses a variety of disciplines: psychology, philosophy, anthropology, ethology, linguistics, computer science, and neuroscience. I have pointed to the importance of a developmental perspective on cognitive science. But what about the converse? What difference does it make whether or not we study developmental psychology from a cognitive science perspective?

Consider this analogy. Computer scientists use computers in two rather different ways: as a practical tool and as a theoretical tool (Rutkowska 1987). When computers are used to solve practical problems such as designing robots and expert systems, the focus is on successful behavior; how the computer does its job is irrelevant (A. Clark 1987, 1989). Thus, the introduction of a “kludge” (something that remains unexplained but that works for a particular task) poses no problem. But when modelers use computers as theoretical tools for simulating mental processes and testing psychological theories, the focus shifts to questions about appropriate architectures and mech-

anisms and about the nature of representations. How the computer does its job then becomes a central concern.

Similarly, developmental psychologists fall, *grosso modo*, into two categories: those who see the study of children as an end in itself and those who use it as a theoretical tool to understand the workings of the human mind in general. In the former case, as mentioned above, many developmentalists focus on behavior—e.g., on the particular age at which the child can do X. Decades of developmental research were wasted, in my view, because the focus was entirely on lowering the age at which children could perform a task successfully, without concern for *how* they processed the information. I once began an article (Karmiloff-Smith 1981, p. 151) as follows: “The enticing yet awful fact about child development is that children develop! Awful, because it has provoked a plethora of studies, totally unmotivated theoretically, accepted for publication in certain types of journal because the results are ‘significant’—significant *statistically*, since it is indeed easy to obtain differential effects between, say, 5 and 7 year olds, but questionable as to their significance *scientifically*.” Fortunately, however, the study of children is used within a cognitive science perspective also—i.e., as a theoretical means of understanding the human mind in general. In such work, the focus is on the initial architecture, the processing mechanisms, and the nature of internal representational change.

Many recent books and articles have focused on what cognitive science and information-processing models might offer the study of development (Bechtel and Abrahamsen 1991; A. Clark 1989; Klahr et al. 1987; Klahr 1992; McTear 1987). In this book, my aim is to highlight why a developmental perspective is essential to cognitive science.

### *The Plan of the Book*

The first part of each of the following five chapters—on the child as a linguist, a physicist, a mathematician, a psychologist, and a notator—concentrates on the initial state of the infant mind and on subsequent domain-specific learning in infancy and early childhood. Each chapter then goes on to explore empirical data on older children’s problem solving and theory building, with particular focus on cognitive flexibility and metacognition.

I might have devoted a separate chapter to the child as a concept former, since there has been extensive research on this topic.<sup>29</sup> However, conceptual development is relevant to each of chapters 2–6: how children categorize objects in the physical world, how they mathematize that world, how they conceive of human agents versus physical

objects, and how they encode that knowledge linguistically and in external notations such as drawing and maps. Concept formation will thus permeate each chapter rather than be treated separately.

In chapters 7 and 8 I take another look at the reconciliation between nativism and Piaget's constructivism, and discuss the need for more formal developmental models. Here I compare aspects of the RR model with connectionist simulations of development. At all times, I place particular emphasis on the status of representations sustaining different capacities and on the multiple levels at which knowledge is stored and accessible. I end the book by taking a final look at the RR model and speculating on the status of representations in nonhumans, which—however complex their behaviors—never become linguists, physicists, mathematicians, psychologists, or notators.