

RECENT TRENDS IN COGNITIVE DEVELOPMENT

My goal in this paper is to bring you to the view that the study of cognitive development informs our understanding of the nature of the mind. This position was Piaget's and, although his work has been the subject of much criticism, scrutiny, and debate, on this matter he was right.

The plan of this paper is as follows. I will first go over some old and some new facts about cognitive development. These seemingly contradictory facts lead me to a lengthy treatment of one predominant trend in the current study of cognitive development—the study of structures that are invariant throughout development. Such work highlights how developmental work uncovers facts about universals of cognition. It also provides new insights into what does develop. Next, I turn to the question of how development might proceed. Finally, I summarize what I think are the major trends in cognitive

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development. The major points that arise from my discussion are these:

1. There are many cognitive capacities at a very early age that probably serve to guide development.
2. Most cognitive development is self-motivated.
3. The path of cognitive development is multifaceted and includes (a) increased control over performance constraints, (b) development of access and metacognition, (c) inductions of new principles, (d) construction of knowledge systems, and (e) differentiation and integration of structures and concepts.

Cognitive Development: Old and New Facts

Two of Piaget's best known findings are those about the development of the object concept in infancy and conservation in middle childhood. Piaget found that acquisition of the object concept seems to pass through six stages, taking about 2 years to do so. During stages 1 and 2 (0-4 months), infants stop attending once objects leave their immediate line of sight. During stage 3 (about 4-8 months) infants reach for and grasp visible objects, follow objects as they fall on the floor, and even anticipate their trajectories. But, incredibly, they stop reaching for or looking at an object if that object disappears behind a barrier. An object that once grabbed their attention no longer has any effect on them. It's as if an object is "out of sight, out of mind," as Piaget concluded.

During stage 4 (about 8-12 months) infants will search for and retrieve an object they see someone cover; however, they show a bizarre tendency. If that object is removed from behind the barrier (A) and, while the *baby watches*, is moved behind another barrier (B), the baby searches only behind the first barrier! The infant seems not to realize it is the same object: "The object is still not the same to the child as it is to us: a substantial body, individualized and displaced in space without depending on the action context in which it was inserted" (Piaget, 1954, p. 64).

In stage 5 (12-18 months), despite the fact that children search for the object in that place to which they saw it moved, they do not search for an object that is invisibly moved to another hiding place. They do not seem to believe that the attractive object "has just got to be somewhere." This, Piaget maintained, requires an ability to use symbols to represent the object—an ability that he concluded does not reveal itself until the end of sensorimotor intelligence or stage 6. The conservation findings are similarly surprising. In the number conservation task, children between the ages of 4 and 7 years are shown two rows of objects lined up in one-to-one correspondence.

Having answered correctly that both rows have the same number, they watch as the experimenter transforms one of the rows, usually making it longer or shorter than the other. Once again the child is asked whether both rows have the same number of objects. Children of 6 or 7 years quickly say they do and readily explain why: "You didn't add or subtract any" or "You just pushed them around." In dramatic contrast, the younger child denies the continued equivalence, and claims one row has more than the other. For Piaget this meant that young children believe transformations that alter perceptual features of a quantitative display actually alter the amount therein. In order not to believe this the child is said to have to advance to the stage of concrete operational thought, a stage characterized in terms of the availability of certain mathematical and logical structures. (See Flavell, 1963; Ginsburg & Oppen, 1979; or Gruber & Vonèche, 1977 for details).

These are reliable findings, so much so that I always invite my introductory psychology students to confirm them with children they know. However, when different tasks that clearly test for the same or related abilities are used, different conclusions about the nature of the child's capacities and concepts are reached. Baillargeon's study on the object concept in 5-month-old babies and Gelman and Gallistel's study on preschooler's understanding of number illustrate different conclusions that have been reached.

Baillargeon (Note 1) worked with a procedure commonly used with infants—habituation. Infants were shown a screen that rotated forward and backward through an arc of 180°. As expected, infants who first watched attentively became bored, as evidenced by a 50% drop in their looking times. Once habituation occurred, a yellow cube was placed alongside the screen for two trials of viewing. Then the cube was placed behind the screen and on alternating trials the infant saw a screen that once again rotated through a 180° arc (and at least from the adult perspective seemed to crush the covered object) or a 120° arc, as would be required by the presence of a solid object behind the screen. One-way mirrors and variations in lighting created the visual effects. Despite the fact that infants habituated to the 180° rotation, they now looked longer at it than at the 120° rotation. Why would they do so unless they knew that there was supposed to be a solid three-dimensional object behind the screen and hence were taken aback by seeing the screen rotating through it? Five-month-old babies must believe that objects have permanence—and solidity as well (cf. Locke's definition of the object concept).

I (1978) investigated preschoolers' understanding of number. To assess children's understanding of the role of various transformations, such as lengthening or adding, on the cardinal value of a set, we used a variation on the magic show. In phase 1, our version of the magician's setup, children were shown two plates, each with a different number of objects on them, for example, two versus three toy

green mice. Without mentioning number, we told the children that one of the plates was the "winner" and the other the "loser," and that every time they found the winner-plate they would get a prize. Each child and the experimenter were to take turns either covering up or shuffling the covered plates, after which the child could guess which can contained the winner and then to look and see if he or she was right. Each correct identification was rewarded. In fact, children seldom erred. Because children said that a plate was the winner or loser because of the numerical value therein—"It wins cuz it has three—one, two, three"—we knew they had responded on the basis of number.

Unknown to the child, phase 2 of the experiment started with the experimenter making surreptitious changes in the displays. Depending on the condition and the experiment, a child encountered the effects of adding or subtracting one or more items from a display, such as spreading out a row and making it longer or substituting a different colored or even different type of item. In most experiments small set sizes ($N < 6$) were used.

The results were straightforward. Those children who encountered irrelevant changes deemed them such; those who encountered relevant transformations pronounced them relevant. Thus changes in number elicited considerable surprise: "Eeee, how did that happen?!" Furthermore, the children postulated the relevant transformation: "One gone—Jesus Christ came and took it." They also told us what number they expected and what number they actually encountered. Children in the number-irrelevant conditions as often as not noted the change. When they did, they said it did not matter because the numbers were as expected: "Still three, they just spreaded out." This was even true when the color or the type of object changed.

What can be said of such contradictory findings? To infants, at least, we have to grant that their conception of the world is much more accurate than Piaget, or anyone else for that matter, once thought (cf. Gibson, 1982). Still, it will not do to say we can ignore Piaget; his results are too reliable and too compelling. What we need is a theory that can incorporate the old and the new. The recognition of this state of affairs has created an atmosphere of excitement and theoretical ferment.

What Does Not, What Does Develop

One clear focus of research in cognitive development in the last decade has been the search for mental structures that do not develop. The strategy has been to compare and contrast children of different

ages. This has yielded new insights on the nature of what does develop in particular and on the nature of the human mind in general. To illustrate, I will discuss at length some of the recent work that has been done on classification abilities. A briefer treatment of number and causality will follow.

Classification

Traditional Findings

Piaget's account of the conservation failures of preschoolers uses a stage theory in which children acquire new and qualitatively different mental structures at different points in development. The preschooler is said to lack the concrete operations of classification and ordering structures—structures that are presumed to mediate the ability to solve classification and seriation tasks, and, when classification and seriation tasks are integrated, conservation tasks.

To buttress the conclusion that preschoolers lack concrete operational structures, Piaget pointed to the development of classification abilities, noting the preschooler's inability to consistently apply a taxonomic classification scheme or to make inferences about hierarchical relationships (Inhelder & Piaget, 1964). Similar ineptitudes have been reported by Bruner and Olver (1963), Vygotsky (1962), and Werner (1940). Indeed, the young child's difficulty with classification stands as one of the best documented facts in cognitive development. Rather than use consistent criteria to classify, children organize thematically—they put objects together that make up a building, remind them of a given setting, tell a story, and so forth. Suppose young children were shown pictures of various children, adults, cars, and bicycles. It is a safe assumption that they would put the children with the bicycles and the adults with the cars. In contrast, older children and adults can be expected to put all the people in one pile and all the vehicles in another.

Another aspect of preschoolers' classification schemes is illustrated by their performance on the Piagetian class-inclusion task. When shown a display made up of two different kinds of fruit and asked, "Which has more, the fruit or the apples?" they say, "The apples." They fail to compare the subordinate class with the superordinate class. Despite the robustness of the results on various classification tasks, as I will show in the discussion that follows, it is no longer possible to interpret these results to mean that young children lack the capacity to impose hierarchical organization.

Ontological Knowledge

Keil (1979) provides compelling evidence for the view that an adult's ontological knowledge (knowledge about the basic categories of existence) is hierarchically organized and may be innately constrained. It seems that what objects we know and what we know about them—hence, which predicates we can use when describing them or thinking about them—are organized in a strict hierarchy.

To discover the way we organize ontological knowledge, Keil asked subjects in one experiment to judge what could or could not be predicated about an object. For example, students were asked if it was correct to say, "The lady is not sorry," "The day is an hour long," "The day is heavy," and so on. The choice of sentences was determined by Keil's theory of how we organize our knowledge about ontological categories. This is illustrated in Figure 1 in what Keil calls (following the philosopher Sommers, 1965) a predictability tree. Words in uppercase letters stand for predicates that are true (or not true) of the objects that are shown in lowercase letters. The solid line branches represent categories and subcategories of objects; the dotted lines represent categories and subcategories of predicates. Objects and predicates are organized in a strict hierarchy. Starting at the bottom, people and animals are classified separately as regards the predicates "is honest" and "is sorry." People and animals are classified together but separately from plants as regards the predicates "is asleep" and "is hungry." Moving up the hierarchy, all living things are classified together and separate from all inanimate things, and so on.

This particular predictability tree is more than theoretical. It conforms to how subjects judged the sentences they were given. Hence subjects said that it was all right to say that a man, a pig, a tree, a car, some milk, a storm, and a story can be thought about. However, subjects maintained that events like storms cannot be red or heavy; physical objects can. They also said that only animate objects can be said to be dead, able to breathe, and so forth. This is wonderful evidence that knowledge is hierarchically organized. Interestingly, the same results were obtained cross-culturally.

Keil¹ also found that at least by 3 years of age (the youngest children he has tested), children have predictability trees that are hierarchically organized along the same lines. It is true that 3-year-olds do not have as richly differentiated an understanding about objects in the world as adults do. But their knowledge can be mapped onto the adult predictability tree by simply collapsing some of the nodes in the adult tree. Thus where adults distinguish between plants, animals,

¹There is some recent evidence to suggest that Keil's ontological categories work better for knowledge about objects than for knowledge about events (Mandler, 1983).

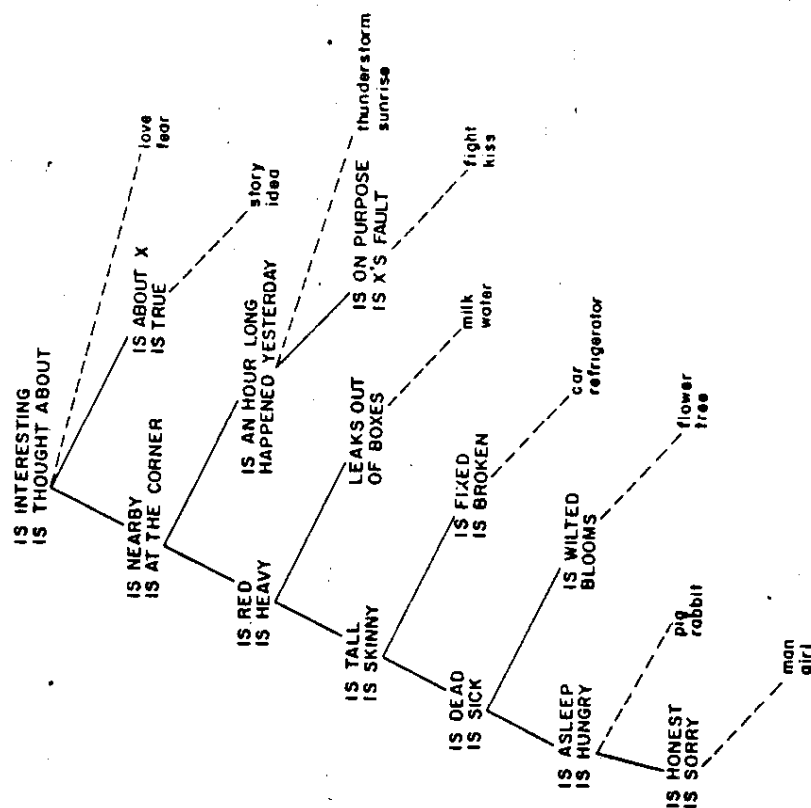


Figure 1. An example of a predictability tree developed by Keil (1979). Reprinted by permission.

and people on the one hand, and natural objects versus artifacts on the other hand, 3-year-olds distinguish only animate objects from inanimate objects. So the child may say that trees can be sorry, but that cars cannot. With development, the child's knowledge of subcategories is differentiated out of the larger categories.

In the last 2 years there has been a spate of other evidence that preschoolers have a hierarchical classification scheme. (See Clark, 1983; Gelman & Baillargeon, 1983; Markman & Callahan, in press; Mandler, 1983, for reviews.) Gelman and Spelke (1981) conclude that what evidence there is supports an innate ability to treat animate and inanimate objects differently. Keil's (1981) conclusion that the development of ontological knowledge is governed by an innate hierarchical organization constraint may be right.

Some Reasons for Failure to Classify

If young children have the capacity to use a hierarchical organization scheme, why do they fail to do so in the tasks used by Piaget, Vygotsky, and Werner?

The Role of Knowledge

Given that the ontological trees of very young children are not as differentiated as those of adults, it is clear that young children simply know less than adults about the nature of objects in the world. Perhaps this is why children fail to employ a classification scheme. As it happens, there are 4-year-olds in this country who have a passion for dinosaurs, there are 4-year-olds in this country who have a passion for learning about dinosaurs and hence provide a test of this hypothesis. Chi and Koeske (1983) have done an in-depth study of one such child in Pittsburgh. When asked to recall the names of the dinosaurs that he knew, the child came back with a list that was hierarchically organized by some very abstract criteria, such as whether or not the dinosaurs were land-living or meat-eating.

Competition From Other Structures

Although young children's limited knowledge-base is surely a factor in their tendency not to classify consistently on the basis of superordinate criteria, it cannot be the only problem. This is because many studies do present children with familiar materials. Recent research makes clear that the failure of young children to use classification is due partly to their preference for other modes of organization.

Collections. Markman (1981) distinguishes between concepts organized as classes and those organized as collections. The difference between the concepts of trees and forests illustrates the distinction. Given a particular tree, one can answer whether or not it is a member of the class trees. However, given the same instance of the same tree, one cannot answer whether it is a member of a forest. There must be other trees nearby; the instance tree is a member of a forest only if it is in proximity to a large number of other trees. Likewise, a particular child can be said to be a member of the class people. But unless one knows that the child has a parent (or other relation) one cannot determine whether that child is a member of the collection family. Markman contends that class terms focus attention on the particular members of a display, collection terms on the totality of the display. Hence, she concluded that young children might be better able to keep in mind the whole of a display when thinking about a part in terms of a collection rather than in terms of a class. Her research suggests that this is so.

Markman and Siebert (1976) tested children with both collection and class terms. As an illustration, when children were in the collection condition they were asked, "Who would have more toys to play with, someone who owned the blue blocks or someone who owned the pile?" When in the class condition they were asked, "Who would have more toys to play with, someone who owned the blue blocks or someone who owned the blocks?" This simple change in wording—notice that the stimuli were identical for the two conditions—produced dramatic differences in the child's ability to indicate that the whole contained more than its subcategories.

There is evidence that children—and adults, if you accept the idea that teenagers are adults—impose a collection organization in a situation where it would seem they would have to impose a class-inclusion one (Markman, Horton, & McLanahan, 1980). For example, Markman et al. tried to teach subjects novel class-inclusion hierarchies. Subjects were taught that one subset (A) of novel figures were "zugs," another subset (B) were "laks," and that all of the figures together (C) were "bivs." Then they were tested to determine whether they represented their knowledge in a class-inclusion hierarchy, for example, if they knew an individual zug was also a biv. They did not. Pupils as old as 14 years of age denied that any single element was a biv, and picked up several zugs and laks when asked for a biv. This is akin to denying that a rose or a petunia is a flower and behaving as if a flower was a bouquet—hence the handful of objects when asked for one! In other words, subjects imposed a collection organization rather than a class organization on the materials that were organized (from the experimenter's point of view) in a class-inclusion hierarchy. Such results highlight the fact that part of the reason young children fail to use a class-inclusion scheme is that there are other structural tendencies dominating their minds.

Schemas. Jean Mandler (1981) has proposed that there are yet other modes of conceptual organization that compete with and often override the use of classification. These are organizations based on spatiotemporal relations as opposed to class relations. The fundamental units in these types of organization are not categories but schemas. These have been shown to represent our everyday knowledge of classes of events like restaurant-going; our knowledge of faces; our knowledge of rooms in general and kitchens, bedrooms, and bathrooms in particular; our knowledge of folktales and story grammars; and so forth (Bartlett, 1932; Bower, Black, & Turner, 1979; Bransford, 1979; Mandler & Parker, 1976; Rumelhart & Ortony, 1977; Schank & Abelson, 1977; Stein & Trabasso, 1982).

The evidence that adults use structures that capitalize on spatial or temporal relations is extensive. For example, we retain a general script for restaurant-going and hence can make inferences about less than complete accounts of activities in a restaurant. Thus, even if I were not told that a waiter took orders before removing menus from

people's plates, I would still be able to say this was so. Correctly or not, I would infer it from my restaurant script. The fact that we have a schema for a room will lead us to misremember a scene that shows chairs on walls; we normalize our memory to place them on floors where they belong (Biederman, 1982; Mandler & Parker, 1976). Our use of story grammars often underlies our falsely remembering material that was not in fact in a given story, introduces intrusions in our recall, alters the order of input toward the canonical form dictated by the underlying grammar of the story, and leads us to summarize for gist (Mandler, 1983; Stein & Trabasso, 1982).

Recall the example of the preschooler who put pictures of children with pictures of bicycles and pictures of adults with pictures of cars. Rather than saying the child lacks a classification structure we could say the child took the opportunity to use scripts about who uses what forms of transportation. To support this line of argument, it is necessary to show that preschoolers do indeed share adults' predilection to form event schemata and, when given a choice, use them as opposed to classification structures. Evidence supporting the use of either schema is available.

Nelson and her students (Nelson & Gruendel, 1981) found that children as young as 3 years have well-ordered scripts for a variety of the classes of events that make up parts of their lives, including restaurant-going (especially to McDonalds) and lunch at school. And they, like adults, misremember the order in which they recall because of a powerful tendency to make the input conform to canonical order. Mandler, Bates, Gerard, & O'Connell (cited in Mandler, Note 2) are now finding evidence for the presence of event schemata in 1½- to 2-year-olds. Toddlers were asked to imitate event sequences that were well ordered, reversed, or incorrect. An example of a well-ordered sequence was a teddy bear placed in a tub, then washed, and then dried. The children did best on the well-ordered sequences and, most significantly, reordered other sequences to conform to a canonical order.

The work on story grammars adds weight to the conclusion that event schemata are available to young children. Poulson, Kintsch, Kintsch, and Premack (1979) found that 4-year-olds used a story schema to "read" a series of pictures. Mandler and Johnson (1977) found that children, like adults, invent story-appropriate material when they cannot recall what they were told. These authors, as well as Stein and Glenn (1979), report that children are much better able to remember material in canonical order; indeed, Mandler (1979) points out that the younger the child the more dependent he or she is on receiving well-ordered material. Finally, Mandler, Scribner, Cole, and DeForest (1980) obtained identical patterns of recall in children and adults in this country and in Liberia. In the latter case, it did not matter whether the children were schooled or whether the adults were literate.

Smiley and Brown (1979) gave subjects classification materials that could be sorted thematically or taxonomically. Preferences for sorting materials into thematic as opposed to taxonomic groupings showed a curvilinear relationship across age: Preschool children and older adults preferred thematic categories. In follow-up tasks that required subjects to sort another way or showed the experimenter first modeling a taxonomic solution it was established that these were only preferences. Hence, there is evidence that young children's tendencies to produce arrays that tell stories may be due in part to their greater preference for organizations that rely on spatial or temporal relations, rather than to an inability to use organization according to classes.

Wholistic as Opposed to Analytic Responses to Stimuli. There is yet another kind of competing structural tendency that has been suggested as a possible source of interference; this is to respond to stimuli in an integral or wholistic fashion. Smith and Kemler (1978) found that young children do not typically analyze stimuli into the dimensions represented in the stimulus. Thus children compare stimuli on the basis of overall similarity rather than on common values of a specific criteria. This is akin to comparing people not on the basis of hair color but instead on the basis of what they "sort of look like."

If young children are disinclined to analyze stimuli in terms of component dimensions, then it is hardly surprising if they are disinclined to apply a hierarchical classification scheme in a sorting task. To do the latter the child must select criteria that are common to subclasses of objects and that distinguish the subclasses from each other.

I point out that I have characterized the young child as disinclined to analyze stimuli—not as unable to. As Kemler and Smith (1979) point out, it is possible to show that young children can employ a dimensional structure of stimuli but that such access is limited to specific conditions. The notion of access has come to play a central role in current theorizing about the nature of cognitive development. I bring this to your attention here and will return to it.

The Function of Classification Structures

If hierarchical classification structures are inaccessible or likely to lose out to competing structures, why does the young child have them at all? One answer is that these structures facilitate syntax acquisition (Fodor, 1972). Keil (1981) offers another likely answer, at least with regard to the claim that humans are constrained to organize their ontological knowledge in a hierarchical fashion. Children learn words at a phenomenal rate (Carey, 1978), but why this is so has been puzzling. According to Keil, childrens' knowledge of predicates is such

that if children hear "the gub is sorry" they can infer that whatever gubs are they move on their own, eat, sleep, and so forth. In short, children can know a lot about what "gub" does and does not mean. Carey's results (Note 3) support this conclusion. She taught preschool children that a given animal (for example, a dog or a human) had a "spleen." Children were then asked whether each of a series of objects such as an aardvark, a fish, a bug, or a mechanical monkey, had one. Whereas children's willingness to grant this organ to other animals depended somewhat upon the similarity of that animal to a dog or human, they never attributed the spleen to inanimate objects.

Access

I draw attention to the fact that the situations in which young children reveal their competencies with hierarchical classification schemes are natural situations in which children go about the normal business of developing language abilities and learning about objects in everyday life. Perhaps we uncover hierarchical classification capacities in these domains because these are the domains within which we were programmed to use these capacities. To explicate, consider Rozin's account of cognitive development.

Rozin (1976) proposed that part of cognitive development involves an increasing ability to access underlying cognitive and perceptual abilities (see Fodor, 1972, 1975, for a similar view). Early and possibly innate abilities are used in only a few or even just one domain. But as development progresses, these abilities are used in more and more settings because of a growing ability to gain access to underlying competencies. Rozin discusses two kinds of access. One is the kind just considered—the ability to employ a given computational system outside of its original evolutionary or ontogenetic domain, independent of whether the routine is used consciously. The other kind of access is the ability to articulate the nature of the principles that underlie behavior. This latter ability is often called metacognition (Flavell & Wellman, 1977; Gleitman, Gleitman, & Shipley, 1972). Pylyshyn (1978) makes a similar distinction between flexible and reflected access. Both are said to result from the development of the access ability.

Situations wherein young children can be shown to use hierarchical classification schemes are predominantly those that do not require the child to access the structure and put it to work in the name of some task demands. It is also noteworthy that situations requiring access, such as list learning or standard classification tasks, are those with which children do poorly. Such observations have led Brown, Bransford, Ferrara, and Campione (1983), Carey (in press), and Mandler (1983) to conclude that part of what develops in the domain

of classification skill is due to access—in both of the senses spelled out by Rozin and Pylyshyn. All theorists maintain that conscious access to, or metacognition about, classification structures is a relatively late development (Flavell & Wellman, 1977). Brown and Mandler also focus on the gradual increase in the flexible use of classification. Later in this essay we shall hear more of the idea that with developing cognitive and perceptual competencies.

A Return to the Traditional Findings

We researchers have come a long way in our pursuit of an explanation of the nature and development of hierarchical classification structures. We believe that these are available at a very early age and serve to organize acquisition of knowledge about ontological categories and about vocabulary. In pursuit of the answer to why hierarchical structures might not be elicited in traditional classification tasks, we discovered that young children also have available other structures that they use to organize their knowledge. These include collections, scripts, story grammars, and other schemata. We have also uncovered some insights about the nature of what does develop, including the knowledge base, wider access to reasoning principles originally employed only in sharply restricted domains, and metacognition.

Early Number Knowledge

Because number concepts are abstract concepts, they are late to develop—or so reasoned many who wrote about the development of number concepts. But however compelling such reasoning might be, it is surely wrong. It now seems that the ability to count and do simple arithmetic problems may be as natural as the ability to speak a language.

I have already said that preschoolers have a number invariance scheme, by which they correctly classify number-relevant and number-irrelevant transformations. Thus children treat addition and subtraction as operations that alter the value of a set and operations like rearrangement, lengthening, and item substitution, as ones that do not. What I did not say is that they use counting as an algorithm when solving the problems they confront in the magic tasks as well as in other versions of addition and subtraction tasks (Groen & Resnick, 1977; Ginsburg, 1977; Siegler & Robinson, 1982; Starkey & Gelman, 1981).

The conclusion that preschoolers use a counting algorithm to solve addition and subtraction problems may be surprising. You might think that when children count they simply recite the count words from rote memory. But they do not. They have considerable implicit knowledge of the principles that govern counting. Gelman and Gallistel (1978) concluded that preschoolers' understanding of counting is governed by five principles:

1. the one-one principle—every item in a display should be tagged with one and only one unique tag
2. the stable order principle—the tags must be ordered in the same sequence across trials.
3. the cardinal principle—the last tag used in a count sequence is the symbol for the number of items in the set
4. the abstraction principle—any kinds of objects can be collected together for purposes of a count
5. the order-irrelevance principle—the objects in a set may be tagged in any sequence as long as the other counting principles are not violated.

Very young children honor these principles in their counting but do not articulate them—that is, they have little or no metacognitive access to them.

Gelman and Meck (1983), while looking for other performances in which children employ these counting principles, reasoned that if preschoolers know the counting principles, they should recognize counting errors. Separate studies tested for their ability to monitor a puppet's application of the one-one, stable-order, and cardinal principles. Error trials in the one-one experiment included the puppet skipping an item. In some trials of the stable-order experiment, the puppet used a list wherein the conventional order of two tags was reversed (e.g., 1, 2, 4, 3, 5, 6). In the cardinal task, in response to the question "How many is that?" the puppet sometimes gave an answer of one greater than the correct number or even some irrelevant property of the last object tagged. Test trials used set sizes ranging from 5 to 20. The larger sets were substantially greater than these young children could count accurately.

The children did very well at declaring trials correct or incorrect in all studies and on all set sizes. For example, in the cardinal task, after the puppet counted and then answered the "how many?" question, children were asked if they wanted to change the puppet's answer whenever they said the puppet was wrong. The 4-year-olds attempted to correct 90% of the puppet's error trials and 93% of these attempts were correct. The 3-year-olds attempted a correction on 70% of the puppet error trials and 94% of these were correct! Thus very young children use the counting principles to judge the counting of others.

I turn now to my claim that the ability to count and do simple arithmetic tasks is universal. First, it appears that most cultures do use

a counting procedure. It was once commonplace to assign "primitive" numerical abilities to those from nonliterate cultures (Menninger, 1969). Zaslavsky's (1973) work shows, however, that Africans do count and have done so for centuries. A failure to recognize this was due in part to a failure to realize that one does not have to count with words that are reserved solely for that purpose. Saxe (1979) provides a relevant case in point. He reports that the Papua in New Guinea use the names of their fingers and successive parts of their arms and torso as counting tags. This system is illustrated in Figure 2.

Ginsburg (1981) shows that unschooled children of the Dioula (a West African group) know informal mathematics at a comparable level to that of preschoolers in this country. For example, these unschooled African children use comparable counting strategies to solve simple arithmetic problems with concrete objects.

Starkey, Spelke, and Gelman (in press) have determined that 6-month-old babies can respond intermodally to numerical information. Infants in their studies were shown slides of two- and three-item displays made up of a heterogeneous collection of common household objects such as a comb, cup, glass, sponge, and so on. On each trial, one slide of each set size was displayed side by side. Between the two slides a loud speaker emitted the sound of two or three drum beats. Incredibly enough, babies had a significant tendency to look to the slide that had the same number of objects as there were drum beats. Prior work by Strauss and Curtis (1981) and by Starkey, Spelke, and Gelman (Note 4) showed that babies abstracted number across heterogeneous visual displays like those used in the intermodal study. It seems that they can also do so across the visual and auditory mode.

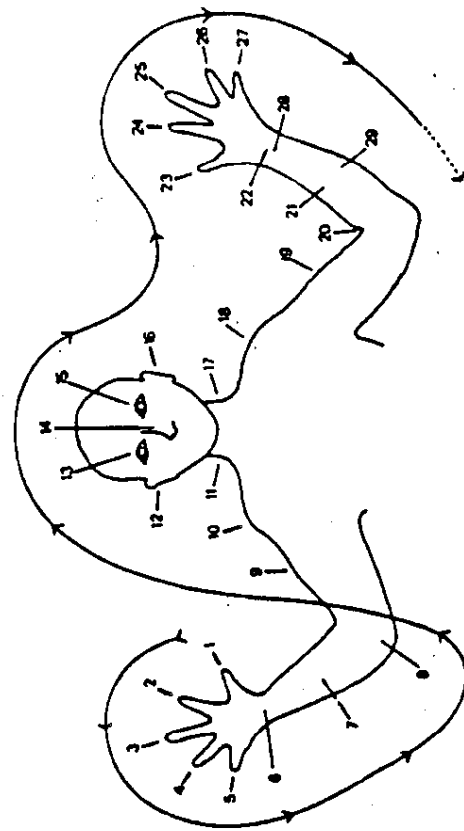


Figure 2. Illustration of the body-part counting sequence used in Papua, New Guinea. Based on a diagram from Saxe (1979). Reprinted by permission.

I confess that I do not have an account of why babies bother to attend to numerical information. Because they do, weight is given to the conclusion that number is a natural domain of cognition.

Development of Counting-Based Knowledge

Narrowing the Gap Between Competence and Performance

When preschool children do the counting themselves, their accuracy falls off rapidly around set size 5. Gelman and Meck's failure to find an effect of set size when children judge the counting of a puppet is the exception to the rule that young children's prowess with numerical tasks is limited to small set sizes (Descouedres, 1947; Gelman & Gallistel, 1978; Schaeffer, Eggleston, & Scott, 1974). Why the difference?

In the error detection tasks children did not have to generate the counting performance, they only had to monitor for conformance to the principles. When counting on their own, children have to keep track of which items have been and have yet to be counted, generate the count list, coordinate the recitation of tags with the pointing to or touching of each item, and remember to repeat the last tag to indicate the cardinal value of the set. Removal of these performance demands had a profound effect, confirming our view that the young child needs to practice counting in order to achieve skill in applying the principles. Like others (e.g., Shiffrin & Dumais, 1981), we are of the view that practice serves to automatize—in this case, the act of counting. The result of practice is that children not only count without error, they count larger set sizes and better remember the goal of determining the last tag. In other words, part of what develops is skill in dealing with the host of performance demands that we all encounter.

The idea that gaps between competence and performance are traceable partly to the lack of automatization of requisite skills figures centrally in several accounts of cognitive development. Case (1974, 1981) and Pascual-Leone (1970) talk of the limits of M-space or working memory and how these limits restrict the number of items in a task or the number of structures a child can work with at once. Shatz (1978) showed that many of the preschoolers' difficulties on communication tasks are due to the performance demands of these tasks. All of these theorists argue that processing space is freed up as a child becomes facile with the responses required. For further discussion of the role of information-processing constraints in cognitive development, see Siegler (1983) and Sternberg and Davidson (in press).

Induction of New Principles

Practice is not the only way one circumvents processing constraints. We also get around memory constraints by imposing organizations on the material we have to remember. If the difficulty of learning to count from 3 to 20 were any predictor of the difficulty of learning to count from 20 to 1,000, it is a safe bet that very few humans would ever learn to count to 1,000. But humans never construct a list of 1,000 number words by brute force. They invariably fasten on a generative scheme involving one or more number generating bases (Zaslavsky, 1973). Such schemes permit the generation of indefinitely long lists of tags by the lawful combination of the relatively few tags in the base set. It is the rare preschooler who has caught on to the base structure and hence acquired the ability to count, in principle, forever. The induction of the generative rules does not usually occur until 5 or 6 years of age (Siegler & Robinson, 1982). Given the ability to count to an indefinite number and the proclivity to do so, the child can go on to induce yet another rule, that the numbers never end (Evans & Gelman, Note 5).

From Implicit to Explicit Knowledge

I have been referring to knowledge of the counting principles as implicit knowledge. I mean to say that the young child's knowledge of counting principles is much like his or her knowledge of language. It will be a long time before the child who says "wented," "goed," "undoed," and so forth can explicate the implicit knowledge of the language that governs the production of such overgeneralization errors. With development, at around 5 to 7 years of age, there will emerge metalinguistic, or explicit knowledge of some rules of the language (Gleitman, Gleitman, & Shipley, 1972). Likewise, there is a trend from implicit to explicit knowledge of the counting principles. The work of Saxe, Sicilian, and Schoenfeld, (Note 6) helps illustrate this point for the stable order principle. They had children watch two puppets count, one using the conventional count list and one using the alphabet. It is not until children are school-aged that they are able to say that an errorless sequence involving the alphabet is better than an error-prone sequence with the count words. Why? To do this children have to explicitly realize that the choice of tags is completely arbitrary. Metacognition about the arbitrariness of symbols is well known to be a late development (e.g., Piaget, 1929; Osherson & Markman, 1974/1975). Not too surprisingly then, success on the Saxe et al. task is late as well.

Conservation Revisited

If the young know so much about numbers, why do they reliably fail the number conservation task? The reasons are many, including the way children interpret the task (Donaldson, 1978; Gelman, 1978). I will focus on but one reason why young children fail.

To successfully perform the number conservation task, the child has to know that whenever the items in one set can be placed in one-to-one correspondence with those in another set, both sets have the same number. This is the set-theoretic definition of numerical equivalence and Piaget assumed that it was the foundation of the child's understanding of number. I have argued that this concept of numerical equivalence requires an explicit understanding of one-to-one correspondence whereas numerical equivalence based on counting does not (Gelman, 1982). With counting a child need not realize that the tags used to count one set can be placed in one-to-one correspondence with those used to count another set. If we assume that the conservation task taps the child's explicit understanding of the role of one-to-one correspondence, then the young child's failure to conserve spontaneously is not in conflict with the conclusion that children know much about numbers. It also suggests that were children's attention focused on the role of counting in establishing the equivalence of the cardinal values in pairs of displays, their implicit knowledge of one-to-one correspondence would become explicit and thus they might conserve. This proved to be the case with 3- and 4-year-old children who, after a brief pretesting experience designed to help them establish this equivalence, were able to conserve and to tell us why they did (Gelman, 1982).

Given these findings, a resolution can be made between the results of recent work on number concepts in young children and Piaget's work on conservation. The initial understanding of number is based on the counting principles and not the logic of classes. Since the principle of one-to-one correspondence is implicit in the counting principles, the latter provide the foundation from which an explicit understanding of the logical principle of one-to-one correspondence can be accessed. (Gelman & Gallistel, 1978; Greeno, Riley, & Gelman, Note 7).

Again, then, we see that the pursuit of what does *not*, as well as what *does*, develop has informed our understanding of cognition and cognitive development. Number seems to be a natural domain of human cognition. The development of number understanding involves (a) closing the competence-performance gap, (b) acquiring new rules and principles, and (c) making explicit what was once implicit.

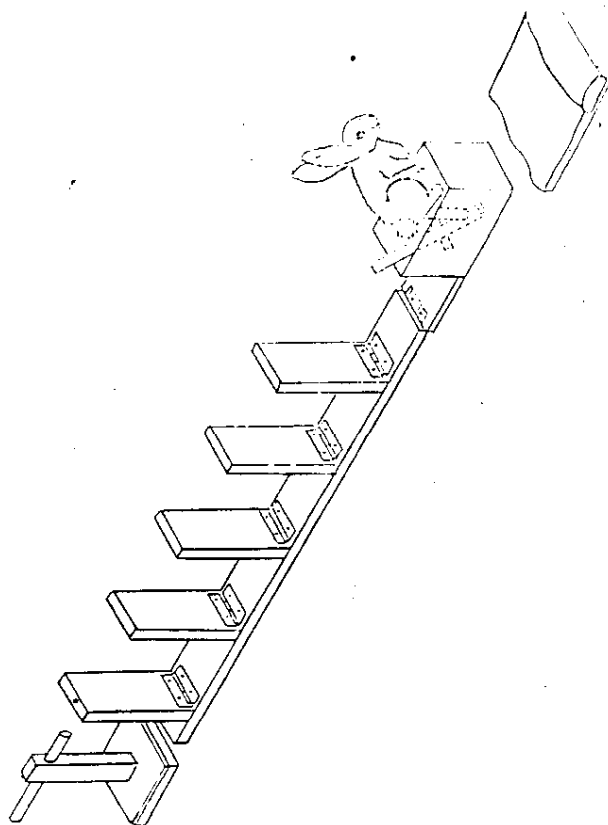


Figure 3. The Fred-the-rabbit apparatus used in the Baillargeon et al. (Note 8) study of causal reasoning in preschoolers.

Causality

In his early studies of the young child's understanding of physical causality, Piaget asked children to explain a variety of natural and mechanical phenomena, for example, the cycle of the moon, floating objects, the movement of clouds, the operation of steam engines and bicycles, and so forth. Analysis of the explanations led Piaget to characterize the young child's thought as fundamentally pre-causal. Thus he wrote that "immediacy of relations and absence of intermediaries . . . are the two outstanding features of causality around the age of 4-5" (Piaget, 1930, p. 268). The young children in his studies said that the pedals of a bicycle make the wheels turn without being in any way attached to them, that a fire lit alongside an engine makes the wheels of the engine turn—even if it is 2 feet away, and so on.

The idea that an assumption of mechanism is lacking in the preschooler is contradicted by several lines of research. I will share two with you.

Baillargeon, Gelman, and Meck (Note 8) showed 3- and 4-year-old children how a 3-part apparatus worked (illustrated in Figure 3).

The first part was a wooden rod that could be pushed through a hole; the second part was a set of five upright blocks and a lever protruding from a box; and the last part consisted of the lever's box with a toy rabbit (called Fred) sitting on top of the box, which was beside a toy bed. When the rod was pushed through the hole it hit the first block, fell. The first block fell and created a domino effect until the last block fell and depressed the lever. The depression of the lever caused Fred—the rabbit—to fall into his bed. After a working demonstration, the children were asked to predict whether Fred would fall into his bed given variations in different parts of the apparatus. Modifications were of two types: relevant ones, which would disrupt the sequence; and irrelevant ones, which would not. For example, substitution of too short a stick was a relevant change; substitution of a glass tube that could reach the first block was an irrelevant change. Similarly, the removal of one intermediate block was a relevant change; covering an intermediate block with cloth was an irrelevant change. In one experiment, prediction trials were run with a fully visible apparatus. In a second, the intermediate portion of the apparatus was screened.

If young children wrongly believe that the occurrence of the first event in a causal sequence is sufficient to bring about the final event, they should treat all modifications in the apparatus responsible for the first event as potentially disruptive and all modifications of the intermediate part of the apparatus as nondisruptive. On the other hand, if children do understand that the intermediate part of the apparatus and the consequent events effectively connect the first and last events in the sequence, then they should regard only the relevant modifications—whether of the initial or intermediate events—as likely to disrupt the sequence. In the first experiment all children were correct on at least 75% of their 24 predictions. In the second experiment, where the screen blocked the intermediate mechanism, all but one child met the 75% criterion. Differential predictions at this level of accuracy could have occurred only if the children recognized the intermediary events as such.

Shultz (1982) showed that even 2-year-olds assume that a cause produces its effects via a transmission of force, whether directly (as when one ball hits another) or indirectly through an intermediary. In Shultz's experiments children were first shown a cause-effect sequence, for example, the turning on of a blower that extinguished a lighted candle. They were then shown two potential energy sources for the outcome: one white and one green blower, each surrounded on three sides by a plexiglass shield. The critical difference between the two blowers was whether the open side was facing a lighted candle and therefore could blow out the candle. If considerations of mechanism do not influence young children, they should have chosen randomly between the two blowers as cause. They did not. Instead they

systematically chose the blower whose opening faced the candle. Similar findings were obtained by transmitting a sound source from a tuning fork and transmitting light from a battery. The consistent result was that children took note of barriers that would stop the transmission of the requisite energy. Of considerable note is that similar results held in Schultz's studies with Mali children in West Africa—whether or not the children were in schooled environments.

My colleagues and I (Bullock, Gelman, & Baillargeon, 1982) have argued that the young child also assumes that causes must precede their effects (the priority principle) and that effects have causes (the principle of weak determinism). To grant these causal principles is not to say that children know that they use them—we doubt that most adults know when they are using these principles. Again, my colleagues and I allow for the implicit use of rules that guide the way the child interacts with his environment without assuming explicit or meta-cognitive knowledge of these principles.

Again, to say that the young child has some competence is not to say that he or she has a complete, correct understanding of physical causality. As Baillargeon (Note 9) shows, the development of the ability to explain why a prediction is correct evolves very slowly. Even undergraduates at Johns Hopkins University make erroneous assumptions about the way the world works (McCloskey, 1983). Their predictions about how objects will move are more consistent with Aristotle's and the Medievalists' writings on physics than anything Newton ever wrote—never mind Einstein. Wrong theories abound in the history of science, but whatever the theory, assumptions must have been made about priority, mechanism, and determinism or there could hardly be a history of science. Like Carey (in press), we hold that Piaget's experiments on causal reasoning should be viewed as experiments on the acquisition and adaptation of an explanation system, on the concept of explanation, and on the notion of what constitutes an explanation (Bullock et al., 1982). When viewed from this perspective, it is possible to allow that there are qualitatively different theories of physical reality as a function of development or schooling. It is not, however, necessary to deny that the young or uneducated have causal attitudes that are governed by implicit principles of causal reasoning.

There is much more early competence than once assumed. Converging cross-cultural findings point to the fact that there are natural, universal domains of cognition. The whats of development are many, including an expanding knowledge base, an increasing skill at applying existing competencies, an ability to access in some domains and apply them to another, and metacognition. Elsewhere I have argued that these natural competencies guide development within their domain. This brings me to the "how" of cognitive development.

Assimilation and Accommodation

Brown et al. (in press) point out that studies of children's learning during the past decade have emphasized the learner as an active rather than passive recipient of environmental input. Indeed, I should note that the same is true of the study of adult learning and cognition. Theorists like Bransford (1979), Marshall and Morton (1978), and Rumelhart and Ortony (1977) have drawn attention to the need to give the learner schemas that serve as sources for monitoring his or her learning as well as for determining what an individual will perceive. I like to think of these theoretical developments as the developmentalization of learning theory and cognitive psychology. For within the context of developmental theories—particularly Piaget's and Werner's—the learner was always an active, controlling participant in the process of learning (see White, 1970, for a review of genetic theories of learning).

My readers may recall the key concepts in Piagetian theory—assimilation, accommodation, and equilibration. Simply put, assimilation is the incorporation of external stimuli into existing schemes or structures. The environment is structured by, or adjusted to, the individual. In accommodation, the individual's schemes adjust themselves to the demands of the environment. Furthermore, Piaget postulated that every structure tends to "feed" itself, that is, to incorporate into itself external elements that are compatible with its nature. The child's schemes are thus seen as constituting the motivational source, or the "motor" of development. Schemes do not merely constrain the nature and range of exchanges children have with the environment; schemes actively bring about such exchanges in their efforts to "feed" or "actualize" themselves. In Piaget's view then, children's activities are necessary in that they help provide input to children's schemes. In short, assimilation and accommodation are the processes that allow children to self-regulate learning and development. In the next section of this essay I focus on why, despite the vagueness of ideas about self-regulation, they are necessary to an account of how development proceeds.

Gelman and Gallistel (1978) argued that the counting principles constitute a scheme that assimilates and accommodates, guides and motivates development. Consider the case of a 2½-year-old child who said, "2, 6, 10, 16," when engaging in what appeared to be counting. When shown one object and asked how many there were, the child said, "Two." When shown two objects and asked how many there were the child said, "2, 6, 6" (emphasis on the last digit). Finally, when shown three objects and asked to count them the child said, "Ten." This child can be said to have applied all of the how-to-count principles because one unique tag was assigned to each object, the same list

was used over trials, and the last tag was repeated in a count to indicate the cardinal number. Obviously the counting principles structured and guided the child's counting performance. The child certainly did not hear anyone count like this.

The children who use nonconventional or idiosyncratic count lists (my favorite is 1, 2, 3, 4, 5, 6, 7, H, I, J) do not do so because they have been taught to use them or have heard them. They must have created these lists using whatever they could find in the environment. In our culture the two obvious candidate lists are the alphabet and the counting numbers. The creation of these nonconventional lists points to the presence of a scheme that requires the count list to have a stable order, but leaves unspecified the nature of the items that constitute the list. What we have then is a principle in search of a list. The principle assimilates items that have a stable order.

Another source of evidence that the counting scheme serves a motivating function is that young children appear to have a compulsion to count, be it cows they pass while in a car, or toys, candies, leaves on a tree, and so on. Because young children are not instructed to practice counting, a theory based on extrinsic motivation would be on shaky grounds. But if we allow that the motivation comes from the structure itself, that is, that the structure prompts the child to assimilate stimuli that are compatible with the structure, then the child's motivation to count can be easily explained.

Children who use an idiosyncratic count list will have to give it up and learn the conventional one, otherwise they will not be understood by others. That is, they must accommodate and adjust their principles to the demands of the environment. I recently came across an example of accommodation in action. A.E., a 24-month-old precocious counter, had been in the habit of practicing her count list: "1, 2, 3, 4, 5, 6, 8, 9, 10." For some time, and to no avail, her mother had been pointing out that she left out the 7. But later the child was overheard to say "1, 2, 3, 4, 5, 6, 8, 9, 10—where's the 7?" For a week thereafter, A.E. counted only up to 6, as if to indicate that she knew she had to make a change. Finally, A.E. resumed counting past 6, with 7 in the list.

Saxe (1982) has documented another example of the accommodation and development of a count list. Earlier I referred to the body-part list used by the Papua in New Guinea. Until recently the list had 53 entries with no base rules. But after coming into contact with Australian currency, the Papua started to use a base-20. The source of the base accommodation was probably the currency; the motivation was probably the necessity for the Papua to find a way to deal with the large numbers involved in cash transactions.

There is much work to do in filling in the account of how the counting principles constrain and guide the acquisition of their development. I am concerned that we researchers cannot do the job with-

out notions like self-regulation. Indeed, I believe this is true for many developmental phenomena.

The literature on language acquisition is full of examples of young children monitoring their utterances and correcting some of their errors (Clark & Clark, 1977). Weir (1962) documented the strong tendency of beginning language learners to lay awake at night and practice the sentences and words they learned during the day. Students of motor development have also drawn attention to the effort the young put into practicing and rehearsing their new-found skills without any external feedback (Bruner, 1973). The work of Deloache and Brown (cited in Brown et al., 1983) makes it clear that the same is true when toddlers have to remember where they have left something.

Deloache and Brown devised a version of hide-and-seek in which children aged 18 to 23 months were required to find a toy hidden in a room—behind a chair, under a pillow, inside a closet, and so on. However, they had to wait for some time after the experimenter baited the hidden site. They actively worked at remembering where the attractive toy was; they tended to verbalize about the toy or its hiding place, to look toward the hiding place, to point to the hiding place, to peek, and so on.

To say that there is a ubiquitous tendency for young learners to self-regulate only begins to account for development. For one thing, there are developments within the domain of self-regulation. For another thing, assimilation and accommodation (and related processes) are not the only developmental processes at work; at least two other powerful processes are differentiation and integration. To do justice to these topics, I would need to write yet another essay. Hence, I refer you to the work of Eleanor Gibson (1967) and Keil (1981) on differentiation, and to others like Fischer (1980), Siegler and Klahr (1982), and Rumelhart and Norman (1978) for ideas about integration. For now, I simply acknowledge that there are developments in the domain of self-regulation, which might seem to raise a contradiction between two conclusions I have reached. These are that even very young children regulate their learning yet lack metacognitions (see also Flavell & Wellman, 1977).

In Piaget's letter writings on assimilation, accommodation, and equilibration, he distinguished between autonomous, active, and conscious regulation. The examples about counting and language use illustrate autonomous regulation. Active regulation is said to occur when the learner constructs and tests theories as she or he tries to make sense of the world. Finally, conscious regulation is just that—the explicit invention, modification, and testing of theories about the world of objects and about the mind. For Piaget, each level of regulation emerged out of the former and hence represented progress in the development of the self-regulation function.

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Karmiloff-Smith and Inhelder (1974/75) demonstrate the difference between autonomous and active regulation. They studied the way in which children figured out how to balance varieties of blocks: standard blocks, blocks glued on top of each other, blocks with hidden weights, and blocks that were hollow. With their application of brute force and the resulting proprioceptive feedback, preschoolers balanced blocks rather well. Their persistence and their use of trial and error reflects autonomous regulation. Somewhat older children developed a theory that the blocks balanced at their geometric center. This was true only for the nontrick blocks; applied to the trick blocks the theory would fail. The older children did fail where the young did not, by insisting on following their new-found theory. Hence their conclusion that it was impossible to balance certain blocks. These impossible blocks were set aside as exceptions to the rule—even when, with their eyes closed, they succeeded in balancing them (because they relied on proprioceptive feedback). Armed with this theory, the children continued to try balancing blocks. Eventually, they began to worry about the growing number of exceptions to their theory. They then invented a local exception rule. But eventually the exception rule, too, began to trouble them and so they began to search for a reconciliation of their theories, thus giving evidence of conscious regulation.

The Piagetian work on levels of self-regulation makes clear that there is no contradiction between the conclusions that metacognition is late to develop and that self-monitoring is a ubiquitous feature of very early learning. Piaget's work also underscores Brown et al.'s (in press) conclusion that there is a real need for those who study learning and development to make a conceptual distinction between self-monitoring and metacognition. Not only is one earlier to develop than the other, but these are different activities. Monitoring is an on-line, ever-present, and integral part of intellectual functioning. Metacognition involves having explicit knowledge both of this functioning and of the nature and content of knowledge.

The work by Karmiloff-Smith and Inhelder adds weight to the conclusion that much of cognitive development is self-motivated. In their experiments, no one ever told the child that he or she had an inadequate theory, or indeed that organization was needed to balance the blocks. To Karmiloff-Smith (1979) the child's independent actions reflect a motive to systematize and come to know the very structure that guides the regulation in the first place. Bowerman's (1982) work on semantic development and Newport's (1980) work on the acquisition of sign buttress this conclusion.

Newport found that deaf children of first generation signers acquire a more richly structured language than do their parents. There must be an internally driven motivation to come to know and systematize the structure. How else can the fact that the children take their

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parents' input and rework it in the absence of any models be explained? Bowerman found that during the initial period of sentence production young children use the transitive causal verbs of bring and drop correctly. Then toward the end of their second birthday they switch to saying things like "I come it closer so it won't fall." They also say things like "untie it off," and "are you gonna nice yourself?" (meaning to make pretty with makeup). Bowerman argues that children go from using a local rule to a more general one—in this case about the semantics of causatives. The important fact here is that the local rule allows children to communicate adequately. Hence, their changing to other devices is most readily accounted for by postulating the children's need to master structure.

I draw your attention to a feature that is common to both the Bowerman and Karmiloff-Smith work. Initially a child will do something right; then without any apparent reason, will start to do it wrong. Development is not just a matter of practicing at doing better what is already done right; there is also a tendency to master the system, even if it means living with doing it wrong (cf. Strauss, 1982).

In summation, a major feature of recent theorizing about the how of cognitive development is the granting of an active role to the learner. No one has concluded that all learning and development comes from within, just that a reasonable amount does.

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