2015. Handbook of Child Psychology and Developmental Science (7th Edition, Vol. 2, Cognitive Processes, pp. 469-518). Hoboken, NJ: Wiley, ISBN 978-1118136782. Richard M. Lerner, Lynn S. Liben, & Ulrich Mueller (Eds.), http://www.amazon.com/Handbook-Psychology-Developmental-Cognitive-Processes/dp/1118136780/

CHAPTER 12

# Conceptual Development

VLADIMIR SLOUTSKY

**INTRODUCTION** 469
**What Are Concepts?** 470
**What Do We Want to Understand About Conceptual Development?** 472
**Principles of Conceptual Development** 472
**Structure and Organization of This Chapter** 473
**A HISTORICAL OVERVIEW** 473
**Philosophical Origins of the Study of Concepts** 473
**Early Psychological Theories: The Classical Approach: Piaget and Vygotsky** 475
**Subsequent Theoretical Development: Prototypes, Exemplars, and Theories** 476
**Summary** 477
**MULTIPLICITY OF CONCEPTUAL BEHAVIOR** 477
**Category Learning and Category Knowledge** 477
**Perceptual Groupings, Categories, Concepts, and Conceptual Networks** 479
**Different Kinds of Categories** 480
**Spontaneous Versus Supervised Category Learning** 481
**Summary** 481
**NEURAL BASES OF CONCEPTUAL BEHAVIORS** 481
**Neural Bases of Category Learning** 481
**Differential Maturational Course of Brain Systems Underlying Category Learning** 483
**Neural Bases of Conceptual Processing** 485
**Summary** 485
**CATEGORIZATION IN NONHUMAN ANIMALS** 485
**Summary** 487
**CONCEPTUAL DEVELOPMENT IN INFANCY** 487
**Preverbal Infants Exhibit Evidence of Category Learning** 488
**Preverbal Infants Can Learn Categories Without Teaching or Supervisory Signal** 490
**Controversial Issues in Infant Category Learning** 491
**Summary** 496
**CONCEPTUAL DEVELOPMENT AFTER INFANCY** 496
**The Role of Cognitive and Linguistic Factors in Conceptual Development** 497
**INTERACTION BETWEEN LANGUAGE AND OTHER ASPECTS OF THE EXPERIENCE** 499
**The Development of Semantic Knowledge and Its Role in Conceptual Development** 499
**The Development of Conceptual Hierarchies** 504
**The Role of Categories in Inductive Inference** 507
**Summary** 511
**PRINCIPLES OF CONCEPTUAL DEVELOPMENT** 511
**Principle 1: The Diversity of Conceptual Behaviors** 511
**Principle 2: Simpler Forms Are More Universal; Complex Forms Are More Unique** 511
**Principle 3: Complex Forms of Conceptual Behavior Are Likely to Be Affected by Language and Instruction** 512
**Principle 4: The Structure of Input Matters** 512
**Principle 5: Conceptual Development Progresses From Less Structured Representations to More Structured Representations** 512
**CONCLUDING COMMENTS: FUTURE OF RESEARCH ON CONCEPTUAL DEVELOPMENT** 512
**Structure and Mechanism** 512
**Development** 512
**Biological Foundations** 513
**REFERENCES** 513

## INTRODUCTION

People are remarkably smart: They use language, possess complex motor skills, make nontrivial inferences, develop and use scientific theories, make laws, and adapt to complex dynamic environments. At the same time, they do not exhibit these skills at birth. Each of these skills requires sophisticated *conceptual* knowledge, and one of the most interesting and exciting challenges in the study of human cognition is to understand how people acquire this knowledge in the course of development and learning. In this chapter 1 address this challenge and review research

on conceptual development that contributes to our understanding of these issues. Given the centrality of concepts to human intelligence and the complexity of the issue of conceptual development, there is little surprise that the study of concepts and their development gave rise to many competing theories.

The previous edition of the *Handbook* included a chapter on conceptual development written by Susan Gelman and Charles Kalish (2007) that provided extensive coverage of domains of conceptual knowledge and what children know in these domains. The current chapter has a different focus: It is concerned with *how* children acquire conceptual knowledge and how domains themselves may emerge as a consequence of learning and development.

Although there are multiple theoretical approaches to conceptual development, I organize the material using a particular theoretical framework. In the most general sense, I assume that there are three important aspects to human concepts. First, there is the ability to form categories (or equivalence classes of discriminable entities) by focusing on commonalities and abstracting away differences. For example, dogs are quite different from one another, yet people can treat them as a class. Second, there is the ability to lexicalize some of these categories (e.g., apply the word *cat* to the category of cats) and use the word in reference to an individual and the entire class. As a result, people can refer to entities (even when the entities are not present) as well as to the entire class (e.g., *I have a cat at home and I like cats*). And third, there is the ability to use words as knowledge hubs for accumulating knowledge about these lexicalized categories, and subsequently form more abstract categories and make predictions. For example, having learned that plants and animals are alike in that they need water and nutrients and they grow, reproduce, and die, people may infer that both plants and animals are alive. Similarly, having learned that a cat has beta cells that produce insulin, one may conclude that other cats (and perhaps other mammals) have beta cells as well.

I further assume that the ability to form categories is shared with other mammals and perhaps with other vertebrates, whereas the latter two abilities are uniquely human. Such evolutionary history is not unique to concepts. Although the vast majority of nonhuman animals have a sex drive, only humans have romantic poetry. Similarly, humans are not alone in having the basic drive for food, but only humans developed culinary art. And as there would be no culinary art without a food drive, there would be no lexicalized categories without the basic ability to form categories. Therefore, in this chapter 1 consider the basic ability to learn and use categories as well as the ability to form and use lexicalized concepts serving as knowledge hubs. I also consider how language, instruction, and selective attention transform the former ability into the later ability—the transformation that is at the heart of conceptual development.

## What Are Concepts?

Q1

In his chapter focusing on concepts (Chapter 12 of the *Principles of Psychology*), William James (1890) wrote, "Our principle only lays it down that the mind makes continual use of the notion of sameness, and if deprived of it, would have a different structure from what it has." If the mind is capable of detecting sameness in a diverse set of objects, then a concept is an output of this process. In other words, the mind can treat different things as if they were equivalent in some way. Such mentally created equivalence classes of different things are defined as concepts. Examples vary from *chairs* (obviously, chairs are nonidentical, but merely equivalent in some way) to *odd numbers* to extremely abstract concepts, such as *cause* or *effect*. Although it is a matter of philosophical debate between Nominalists and Realists as to whether abstract equivalence classes exist outside the mind, the existence of concepts as mental entities is hardly controversial. I will not focus on these philosophical debates, focusing instead on how the mind learns, represents, stores, organizes, and uses concepts.

To appreciate the importance of concepts to humans' lives, it is worthwhile to consider the question How would humans' mental life be without concepts? One can find an example in "Funes the Memorious," a short story written by the great Argentinean writer Jorge Luis Borges. In the novel, Borges describes a man, Funes, who had a phenomenal memory and tried building his intellectual life around it, remembering all individual instances, instead of using more general concepts.

> Locke, in the seventeenth century, postulated (and rejected) an impossible idiom in which each individual object, each stone, each bird and branch had an individual name; Funes had once projected an analogous idiom, but he had renounced it as being too general, too ambiguous. In effect, Funes not only remembered every leaf on every tree of every wood, but even every one of the times he had perceived or imagined it. He determined to reduce all of his past experience to some seventy thousand recollections, which he would later define numerically . . . . He was . . . almost incapable of general, platonic ideas. It was not only difficult for him to understand

> that the generic term *dog* embraced so many unlike specimens of differing sizes and different forms; he was disturbed by the fact that a dog at three-fourteen (seen in profile) should have the same name as the dog at three-fifteen (seen from the front) . . . . Without effort, he had learned English, French, Portuguese, Latin. I suspect, nevertheless, that he was not very capable of thought. To think is to forget a difference, to generalize, to abstract. In the overly replete world of Funes there were nothing but details, almost contiguous details. (Borges, 1942/1962, pp. 113–115)

This short passage wonderfully illustrates that human thought cannot be reduced to the ability to remember information. Instead human thought exhibits the ability to abstract – to form concepts and to use them in reasoning. For example, giving a separate name to each instance of a dog might be of little use, whereas learning a more general category *dog* is quite useful. Most importantly, such general categories allow one to propagate knowledge by making inferences and predictions. For example, upon reading in a book that dogs are carnivores, one would expect a newborn puppy to become a carnivore as well. Similarly, upon learning that a cat eats fish, one may expect other cats to eat fish as well. All this may not have happened if a cat eating fish on Tuesday would be identified as a *dax* and the same cat eating fish on Wednesday as a *fep*. Therefore, most nouns, verbs, and adjectives are not proper names identifying unique individuals like Bill or Jane, or unique events like the War of the Spanish Succession, but rather are names for more general classes of items.

Given the importance of concepts to human intellectual life, it is necessary to ask, Where does this ability start and how does it develop? It is also important to ask about the role of words in this process. Do words help people carve up the world and form general categories? Do people apply words to already formed general categories? Or do both processes coexist?

Before attempting to answer these questions, it is useful to consider the scope of the conceptual system. The scope is remarkably broad: It includes the world, the way the world is represented mentally, and the language, with each component having its own structure. First, the world is structured; if it were not, it would have consisted of "a set of stimuli in which all possible stimulus attributes occurred with equal probability combined with all other possible attributes" (Rosch, Mervis, Gray, Johnson, & Boyes-Braem, 1976, p. 383). However, as Rosch et al. (1976) and many researchers since then convincingly demonstrated, stimulus attributes occur in clusters rather than independently of each other. This is particularly true in the biological world, where creatures with feathers are likely to have wings, beaks, and two legs, whereas creatures with fur are likely to have teeth, tails, and four legs. At the same time, some other combinations of attributes never occur: One would be hard pressed to find a griffin—a mystical creature with the body, tail, and hind legs of a lion and the head and wings of an eagle. As argued in this chapter, the existence of such clusters of naturally co-occurring attributes encourages spontaneous category formation.

Mental representations of categories also have structure, and this structure is not necessarily a mirror image of the input structure. For example, many formal theories of category learning presume that the process of category learning is accompanied by changes in attention allocated to different features. To illustrate, if members of one category are black circles and squares, whereas members of the other category are white circles and squares, attention will be shifted to color and away from shape. As a result, the color dimension will stretch (i.e., people will become more sensitive to color differences), whereas the shape dimension will shrink (i.e., people will become less sensitive to shape differences). Therefore, even though the objective structure of the stimulus set is the same before and after learning, mental representation of the set may change. Learning may also result in more structured representations—representations that capture not only the relations among items within a category, but also relations among categories. One way of mentally organizing relations among categories is a *taxonomy*—a hierarchical system of conceptual organization in which more specific categories are related to each other by class inclusion. Different domains may have different structures and these structures can give rise to different mental representations (see Kemp, 2012, for an illuminating discussion).

The structure of the world (both physical and mental) is also reflected in language. First, languages distinguish among lexical classes that denote objects (i.e., nouns), actions (i.e., verbs), and properties (i.e., adjectives), each of which can denote categories in the world. In addition, lexical items form complex semantic networks, which in turn affect the underlying mental representations. As a result, language may affect the creation of categories that would not have been created otherwise. These include fictitious or supernatural entities such as *genie*, *fairy*, or *centaur*; unobservable states such as *thought*, *doubt*, or *belief*; social categories such as *fairness*, *justice*, *liberty*, or *class*; and mathematical, philosophical, and scientific categories such as *number*, *cause*, *ontology*, *force*, or *atom*, as well as ad hoc categories such as *things in my*

*living room*. As argued in this chapter, many naturally occurring categories have enough structure to be acquired spontaneously by a broad range of organisms. At the same time, more abstract categories may require supervision (i.e., often in the form of instruction), a symbol or lexical marker (i.e., language), and—depending on the category—the ability to selectively attend to a small subset of category-relevant features. Therefore, symbols, supervision, and selective attention are at the heart of post-infancy conceptual development: they are largely absent from animal and infant category learning and their increasing presence in children's learning may explain conceptual development.

Given that concepts have multiple contributing components, the study of concepts is an exceedingly large enterprise. Concepts could be studied by examining the structures in the world and the ways these structures affect learning, by examining the way structures are represented mentally, and by examining the ways language represents conceptual structures. Of course, covering all these issues is too large an undertaking for a single chapter. Therefore, the focus of this chapter is more limited in scope—I will focus on the ways structures are learned and represented, the ways language affects these processes, and the ways these processes and effects change in the course of development.

### What Do We Want to Understand About Conceptual Development?

There are multiple ways of structuring a review of conceptual development. One obvious way is to review what kinds of concepts children have at different ages. Such a review would require one to classify concepts into (hopefully) mutually exclusive domains and then sample concepts within each of these domains. John Flavell successfully applied this approach to his chapter on concept development published in *Carmichael's Manual of Child Psychology* (Flavell, 1970). He divided knowledge into mathematical knowledge, knowledge about the world, and social knowledge and reviewed children's accomplishments in each of these domains. However, toward the middle of the chapter he noted,

> Previous chapter sections have reviewed studies of child's developing conceptualization of certain measurable properties of the natural world's objects and events, properties like weight, length, area, time, and velocity. One might equally inquire into his evolving views about these objects and events themselves, as particular phenomena in that world. For example, how do children of different ages interpret the nature, origin, and activity of specific natural entities like shadows, night, sun, clouds, birth, life, death, and so on? There is a potential danger of posing such questions, however, since the number of investigative entities is practically inexhaustible. (p. 1022)

I take his warning seriously: Instead of cataloging children's conceptual acquisitions in different domains, I attempt to examine how conceptual knowledge emerges from simpler processes. With this goal in mind, I first formulate some general principles that guide this review of conceptual development. I then turn to a brief preview of this chapter.

## Principles of Conceptual Development

I begin by providing five principles that guide my review of conceptual development. First, there is diversity of conceptual behaviors that range from relatively simple and universal (such as generalization) to complex and uniquely human (such as conceptual hierarchies of lexicalized categories). Because this chapter is based on the assumption that simpler forms are foundational for more complex forms, I review multiple forms of conceptual behavior. Second, simpler forms are more universal than more complex forms, and they exhibit early onset in the course of individual development. More complex forms are unique to humans; they exhibit late onset in the course of ontogenesis and are likely to depend on other aspects of cognitive development, including the development of attention and memory. Third, the development of more complex forms of conceptual behavior is more likely to be affected by language and instruction than is the development of simpler forms. Fourth, the structure of input matters: Learning of statistically denser categories exhibits early onset, is present in a broad variety of species, and does not require instruction. In contrast, learning of more statistically sparse categories exhibits later onset, may be limited to organisms with functioning prefrontal cortex, and may require instruction. And finally, conceptual development progresses from less-structured representations (which are mostly based on featural overlap) to more-structured representations that may involve hierarchies, taxonomies, and other complex structures. I return to these principles at the end of the chapter.

### Structure and Organization of This Chapter

Having laid out the theoretical principles that guide this chapter, I turn now to a brief preview of the chapter. I begin with an overview of the history of the study of concepts and of theoretical approaches to concepts. I then turn to a discussion of multiplicity of conceptual behavior and to its biological foundations (covering the neural bases of concepts and conceptual behavior in nonhuman animals). In the rest of the chapter 1 focus on conceptual development in humans, covering conceptual development in infancy, the role of language in conceptual development, acquisition of semantic knowledge and of conceptual hierarchies, and the role of concepts in reasoning. At the end of the chapter 1 revisit the principles of conceptual development with which I began.

## A HISTORICAL OVERVIEW

The study of concepts and their development has a long history. Similar to many other fields of study, its study originated in philosophy and for a long time it remained a purely philosophical endeavor. Although many of the questions asked by philosophy have had profound effects on empirical studies of concepts, some philosophical questions do not lend themselves to empirical investigation. For example, questions like *What are concepts?* or *What are concepts for?* cannot be answered in the course of an empirical investigation. Instead, answers to such questions represent assumptions that drive empirical investigation. Therefore, in this chapter 1 review philosophical debates about the nature of concepts only to the extent that they affected the empirical study of concepts or of conceptual development.

### Philosophical Origins of the Study of Concepts

The goal of this section is to summarize some of the major points that affected the study of concepts and of conceptual development. Like many issues in philosophy, the study of concepts goes back to Aristotle, whose views on the matter are summarized (among other places) in his treatise *Organon* (see Barnes, 1995). According to Aristotle, categories (or concepts) are classes of things and are building blocks of propositions. For example, in *Plato is human*, *human* is a class of things and thus is a concept. Aristotle also argued that the membership in a class is determined by a definition of the class. A proper definition identifies *species*—the smallest class a thing can belong to—by referencing its *genus* (i.e., a larger class) and *differentia* or difference (i.e., a distinct property of the species). For example, a human would be defined as an animal (i.e., the genus) that is also rational (i.e., the difference). Therefore, at least in theory, every class can be defined by its genus and the difference. Cast in the more modern terminology, the central idea is that the genus and the difference are separately necessary and jointly sufficient conditions for category membership.

By today's standards, it is not difficult to see that the proposal runs into multiple difficulties. If everything is defined through its genus (or a superordinate class), what do we do when we run out classes? In other words, how does one define classes at the very top of the hierarchy (human → animal →living thing → thing → ?)? Therefore, some categories will remain undefined. And second, the preceding definition is not the only possible one. For example, a human can be defined as a biped (i.e., the genus) that is also featherless (i.e., the difference). However, according to Aristotle, the second definition should be rejected in favor of the first because the genus, the difference, and the species have to be *essential*; whereas being an animal and rational are essential properties of a human, being a biped and featherless are not.

This distinction between essential and nonessential properties seems rather arbitrary and John Stuart Mill (1843) was among those who pointed to the capricious nature of this distinction. In his *System of Logic*, he famously asked, Why is it that the property of being rational is considered an essential property of humans, whereas the property of cooking food is considered merely accidental? One may also add that if "essence" is something that gives rise to every "proper" definition, how does one define essence without making reference to essence itself? And, if essence is not defined, how does one know which properties are essential and which are not? Although this is not a place for a full review of the *Organon*, it is worth mentioning here because of its enormous influence on the psychology of concepts. As argued later, many generations of psychologists believed that human concepts are organized in the Aristotelian manner—they have necessary and sufficient properties.

Locke, in his *Essay on Human Understanding* (1689/1888), made a minor but important modification of the Aristotelian idea of essences. According to Locke, there is a distinction between *nominal* and *real* essences. The term

*nominal* refers to names and *nominal essences* have to do with definition of words. Nominal essences merely determine one's membership in genus or species. Therefore, being a rational animal is a mere definition of a human and thus has to do with nominal essence. In contrast, real essence is a set of causal conditions that makes things what they are. Real essences cause and explain observable qualities, and because being rational requires an explanation (indeed that is what psychology tries to do!) and is caused by something, it cannot be a real essence of humans, but only a nominal essence.

In contrast to Locke, John Stuart Mill (1843) proposed to dispose of the Aristotelian notion of essences and essential properties and substitute for them a distinction between natural (or "Real" in Mill's terminology) kinds and arbitrary groupings, which were later defined as nominal kinds. To qualify as a natural kind, class membership has to communicate multiple common properties in addition to what is communicated by belonging to the class. By that definition, *animal* and *dog* are natural kinds (because members of these categories share many features), whereas *white things* are not. Mill considered a category of *flat-nosed animals* (i.e., animals with a flat nose) and offered the following argument. To determine whether it is a real kind, one must ask this question: Do all flat-nosed animals, in addition to their flat noses, have any common properties, other than those common to all animals? According to Mill, if so, flat-nosed would be a real (or natural) kind; otherwise, it would not.

Having disposed of issues that could not be resolved within the Aristotelian proposal, Mill created difficulties of his own. Most importantly, the distinction between real and nominal kinds hinges on the idea of multiple common properties. But how can one know a priori if members of a particular class have multiple common properties? Should everything be considered a nominal kind unless proven otherwise? And what about classes that have multiple commonalities according to some accounts but not others? Is the *Hell's Angels* biker gang a natural kind? And why would it not be a natural kind, if its members have many things in common that distinguish them from nonmembers? And what about the French culture or polygamous families? Are these natural kinds? The idea of natural kinds has been highly influential in the psychology of concepts and conceptual development, but if one can neither define what natural kinds are, nor determine unambiguously whether something is a natural kind, how can this distinction be used for a psychological theory of concepts? This chapter, therefore, does not consider ideas of essences or natural kinds as grounded in reality but rather as constructs used by some theories. According to this view, in many cases, the question "Is *X* a natural kind?" cannot be answered on the basis of a clear-cut principle or empirical evidence. At the same time, the question of whether children believe that members of category X have many things in common can be answered empirically.

One important commonality between Aristotle and Mill is that both believed that kinds have necessary and sufficient conditions that determine membership in the kind. There are some very compelling arguments behind this proposition, and at first glance, it appears to be a direct consequence of class inclusion, and thus almost a self-evident truth. Take the statement "All humans are primates." Being a primate is a necessary condition of being a human; otherwise there would have been humans who were not primates. At the same time, humans must have something distinct; otherwise humans and primates would be the same class. And if the latter were the case, then "All primates are humans" would be a true statement. Therefore, there must be something that sets humans apart from the other primates. This argument is so lucid that there is little surprise that it has such staying power: It took more than 2,000 years and the genius of Wittgenstein to dislodge it!

According to Wittgenstein's view presented in *Philosophical Investigations* (1953/2010), there are many concepts that do not have defining (necessary and sufficient) features, but are rather organized in the manner of family resemblance. Consider the category of games: One would be hard pressed to find something that is common to all games and distinguishes them from nongames. Instead, different members of the class of games may share some commonalities, but there is nothing that defines the class. Even if one applies a string of Aristotelian reasoning by stating that all games are a kind of human activity, there is still no distinct feature that is common to all games and sets them apart from other human activities, at least, according to Wittgenstein. This proposal has also been very influential in psychology: It inspired the work of Eleanor Rosch and her colleagues (1975, 1976) to consider family resemblance as an organizing principle of categories. Interestingly, as I discuss later, some researchers, such as Vygotsky, formulated principles of family resemblance independently of Wittgenstein. Ironically, the influence of the definitional (or classical) approach was so strong that Vygotsky considered the family resemblance structure to be a property of only immature concepts.

### Early Psychological Theories: The Classical Approach: Piaget and Vygotsky

The philosophical ideas just discussed (recall that these date back to Aristotle) gave rise to the classical approach to concepts. The core idea of this approach is the logic of classes—a foundation of syllogistic reasoning. According to the logic of classes, classes of progressively increasing generality can be created by means of abstraction. For example, a boy (defined as a young human male) can be included in a more general class of human males, which in turn can be included in a more general class of humans and so forth. Therefore, as discussed earlier, membership in a more specific class is defined by a combination of a superordinate class (e.g., being a human male in the case of a boy) and a distinctive feature (e.g., being young). Each is necessary, and the two are jointly sufficient to determine membership in a class.

The logic of classes presumes at least three additional organizing principles. The first is class inclusion: Subordinate classes can be properly included in superordinate classes (all young women are women). Second, any more general (or superordinate) class consists of a finite number of more specific (or subordinate) classes that are exhaustive of this general class. For example, the superordinate class of humans can be broken down into women and men that fully exhaust the class of humans. And finally, the subclasses of a larger class are mutually exclusive—they do not have common members. It is easy to notice that common quantifiers, such as *all*, *some*, and *none*, express all these relations. For example, *all* expresses the relation of a subordinate class to a superordinate class (e.g., all men are humans), *some* expresses the relation of a superordinate class to a subordinate class (e.g., some humans are women), and *none* expresses the relation between the two mutually exclusive classes (e.g., none of the men are women).

If the concepts are classes and mature conceptual organization is governed by the logic of classes, then the theory of conceptual development must explain how individuals acquire the logic of classes. Both Piaget (e.g., Inhelder & Piaget, 1964) and Vygotsky (1934/1986) attempted to provide such an explanation. Therefore, there is little surprise that both authors believed that development progresses from less organized to more organized logical thought, from failing to understand class inclusion and mutually exclusive relations among subsets to appreciation of these relations.

For example, Vygotsky used a task developed by his associate Lev Sakharov, in which participants (children, adolescents, and adults) were presented with a set of items varying in color, shape, height, and area size and asked to sort the items into four exhaustive and mutually exclusive classes. The researchers defined the classes as a combination of height and size dimensions (i.e., tall/large, tall/small, short/large, and short/small), and the participant had to partition the set according to these combinations of dimension values. The participant was first shown a member of one class and asked to select all members of this class; when selection was completed the researcher provided the participant with feedback. The researchers found that, in contrast to mature conceptual behavior, children tend to exhibit thinking in "complexes"—groupings that are based on local rather than global commonalities. One variant of a complex that is worth mentioning is a chain: When a large tall yellow triangle is introduced as a dax, the child may first select a small yellow triangle, then a yellow circle, then another circle but this time blue, and then a blue square. In each of the choices the child is coherent locally, but not globally. On the basis of these and similar data Vygotsky concluded that young children are incapable of forming real concepts. However, there is another way of looking at it: Perhaps children were forming family-resemblance-type categories in which exemplars share some features, with none of the features being shared by all members of the categories.

Note that this work is based primarily on classification tasks. Although these tasks are useful in that they may reveal a limit on the kinds of concepts children may form, they have their critics. For example, it has been argued that classification tasks may underestimate children's concepts: The fact that a child may put together a dog and a bone does not mean that the child considers the two to be the same thing (e.g., Fodor, 1972).

Piaget was also pursuing the development of logic of classes and he focused on class-inclusion relations. He discovered that children have difficulty understanding such relations: for example, they failed to appreciate the constraint that a more general class cannot have fewer members than its subclass. As a result, when presented with three robins and two sparrows, young children could erroneously conclude that there were more robins than birds. Therefore, if concepts are defined as conforming to the logic of classes, it follows that young children do not have true concepts.

Although the idea that mature concepts are based on definitions advanced the study of concepts and their development, by the mid-1970s the classical approach started

running into difficulties. These difficulties and ideas that eventually replaced the classical approach are reviewed in the next sections.

## Subsequent Theoretical Development: Prototypes, Exemplars, and Theories

In their book *Categories and Concepts*, E. E. Smith and Medin (1981) reviewed the status of the classical view as a theory of conceptual structure. They concluded that given a large number of problems that the classical view runs into, it cannot contend for being a theory of concepts. Although I do not fully review these difficulties here (for such a review, see Medin, 1989), I offer a quick reminder of them. First, for most everyday concepts, it was impossible to come up with a set of necessary and sufficient features shared by all examples of the concept. Second, contrary to the classical view that all examples would be equally good instantiations of a concept (because all possess the concept's defining features), observations showed that people treat examples differently, as when they consider an apple to be a better example of fruit than a kiwi. And finally, there are unclear cases that should not exist if concepts are organized in accord with the classical view. For example, should a floor lamp or a rug be considered furniture? Is a rotten egg still food? These and other problems led researchers to consider alternatives to the classical view. Two are the probabilistic and the theory positions, each considered in turn.

### *The Probabilistic Approach: Prototypes and Exemplars*

As summarized by Medin (1989), the probabilistic view holds that many categories are ill-defined, which means that there is no clear-cut category-inclusion rule but rather features are probabilistically distributed within and across categories (hence the name *probabilistic*). In the absence of a defining feature (i.e., a feature shared by all members of the category but by none of the nonmembers), categories are organized according to family resemblance, which means that each shared feature is common to many, but not to all members of the category.

If there are no defining features, how are categories learned? According to this view, categories are clusters of correlated attributes, and people are capable of detecting these clusters (Rosch & Mervis, 1975). While researchers working within the probabilistic approach generally adhere to these ideas, they vary in their proposals about how category representations are formed. Some believe that people form a summary representation of a category that has been referred to as the *prototype*. The prototype can be the central tendency among the category members, the single best example, or the ideal instance that possesses all of the characteristic features of a category. The prototype plays a critical role in categorization decisions: if a candidate item is similar enough to the prototype, it is classified as the member of a category (J. D. Smith & Minda, 1998, 2000).

Another way of conceptualizing probabilistic categories is the exemplar view (e.g., Medin & Schaffer, 1978; Nosofsky, 1986). According to this view, no summary representation is formed and participants keep a memory record of all encountered members of a category, or category *exemplars*. If a new item is seen to be more similar to stored exemplars of the category than to stored nonexemplars, the item is judged to be a member of a category.

These two approaches have complementary strengths and weaknesses, and there is considerable literature comparing the prototype and exemplar approaches (see Wills & Pothos, 2012, for a review). Given that the differences between the two approaches are rather small (especially when both are compared to the other approaches), I will not focus on these differences here. At the same time, it is worth mentioning that some researchers (Murphy & Medin, 1985) have criticized the very principle that gives rise to both approaches. Recall that, according to both approaches, categorization decisions are made on the basis of similarity, but, according to Murphy and Medin, similarity may not be the right theoretical construct to explain categorization in the first place (see Murphy & Medin, 1985). Overall, two lines of arguments have been offered (see Goldstone, 1994, for a summary of these arguments). One argument is that similarity is context dependent. For example, when asked which country is most similar to North Korea, people may choose Cuba if the choice set includes Cuba, Japan, and Thailand, but they may choose Japan if the set includes Cuba, Japan, and Nicaragua (Tversky, 1977). Therefore, similarity may be too flexible to explain categorization. However, categorization is also subject to context effects, and the other argument is that categorization may be too flexible to be explained by mere similarity. Although these arguments appear to cancel each other out, they convinced many researchers to search for alternatives to similarity. One such alternative is the theory-based or knowledge-based approach to concepts.

### *A Knowledge-Based Approach: Concepts Are Organized by Theories*

In this section I provide a brief overview of the theory-based approach to concepts; additional detail on this approach may be found in Gelman and Kalish (2006). Medin (1989) expressed what is perhaps the most central idea of this

approach: "classification is not simply based on a direct matching of properties of the concept with those in the example, but rather requires that the example have the right 'explanatory relationship' to the theory organizing the concept" (p. 1474). Therefore, people may pay attention to clusters of correlated features not because features are correlated, but because correlations suggest that there is an underlying cause responsible for these correlations and people may believe that it is this cause that is the central (or essential) feature that determines the membership in a category. Because people have knowledge or intuition about how different kinds of categories (e.g., natural kinds or artifacts) are organized, they may assume that radically different kinds of features are central for different kinds of categories.

Based on these ideas, some suggested (e.g., Gelman, 2003, 2004) that even young children hold "theoretical assumptions" that drive their learning of categories. These assumptions are likely to be a priori in that they are preconditions rather than consequences of learning. Among the most frequently mentioned assumptions are beliefs that items belong to categories, that natural kinds cohere, and that words denote categories. "… [C]hildren assume that every object belongs to a natural kind and that common nouns convey natural kind status (as well their accompanying properties).... [N]ames are embodiment of our theories" (Gelman & Coley, 1991, p. 190). Another assumption is that features differ in their "centrality" in explaining category membership, and that children assume that every natural kind has the most central feature (or essence) that is the cause of all other features. It is easy to see why these assumptions have been referred as "theoretical" because they are similar to scientific theories in that they, too, posit unobservable constructs whose function is to explain observable regularities.

This approach to concepts presumes that both acquisition and use of even simple categories requires much background knowledge. Although this knowledge-based approach is highly appealing and it has left a large footprint in the study of conceptual development, it is not uncontroversial. One frequent criticism is that it uses complex conceptual knowledge (see the assumptions presented earlier) that itself needs an explanation as an explanatory primitive (see Sloutsky, 2010; L. B. Smith & Heise, 1992; Spencer et al., 2009).

### Summary

For more than 2,000 years the predominant view of concepts was that they are based on the logic of classes and have necessary and sufficient features. These features were believed to determine category membership and to distinguish the target concept from the other concepts. Conceptual development was believed to be a process of acquisition of the logic of classes and of organizing the concepts according to this logic. However, additional work suggested that concepts may not be organized this way: People have many concepts that do not have defining features (or at least experts fail to find them). The demise of the classical view of concepts led to two alternative arguments. Some argued that concepts are clusters of correlated features and that they are organized probabilistically. Others have argued that people interpret feature clusters as caused by deeper features, and they believe that these deeper causal features determine category membership. However, whatever position is taken, it remains necessary to explain conceptual development. When do concepts emerge? How do they change? What is it that develops? These are topics of subsequent sections. The next section reviews the multiple manifestations of conceptual behavior.

## MULTIPLICITY OF CONCEPTUAL BEHAVIOR

Conceptual behaviors come in various forms: They range from more simple, universal, and early emerging forms (i.e., establishing equivalence between nonidentical percepts) to rather complex, uniquely human, and late-emerging forms (i.e., forming a conceptual network in a knowledge domain). There are a number of important (and still unanswered) questions pertaining to the multiplicity of conceptual behaviors. Do more complex forms emerge from simpler forms or are these forms independent? Do simpler forms contribute to more complex forms? And if the answer is yes, how do simpler forms contribute to more complex forms of conceptual behavior? The goal of this section is to capture this broad range of conceptual behaviors and to consider answers to some of these questions.

### Category Learning and Category Knowledge

As I have studied conceptual development, I frequently found myself asking the following question. Is there any commonality between perceptual groupings similar to those presented in Figure 12.1a and young children's intuitions about whether animals and plants are alive? I suspect that I am not alone in asking this question. If there is no

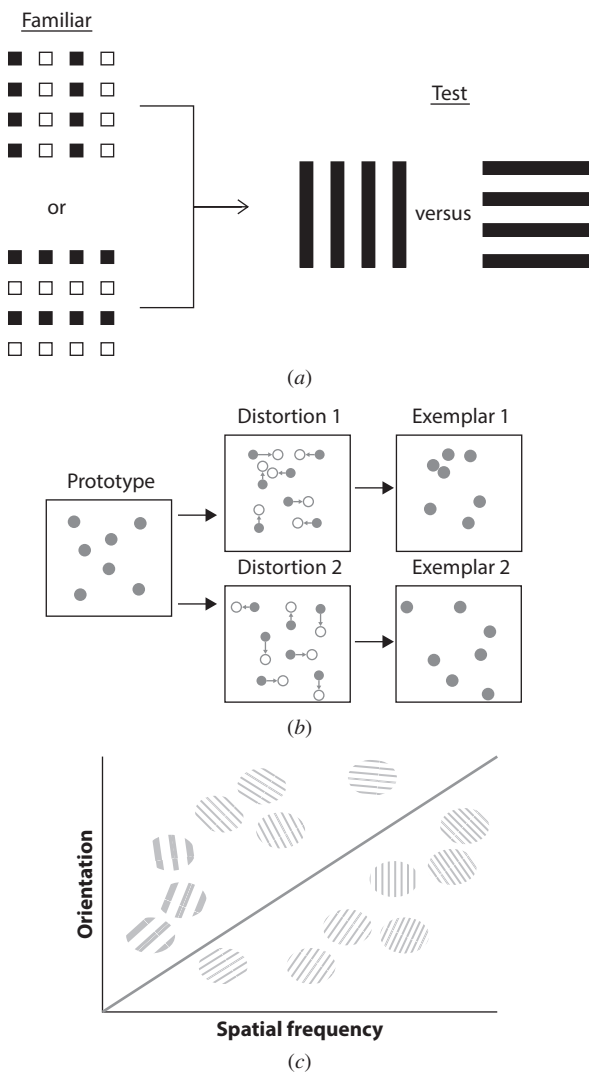


**Figure 12.1** Categorization tasks demonstrating distinction among perceptual grouping, categories, and concepts. (*a*) Luminance-based grouping (reviewed in Bhatt & Quinn, 2010). (*b*) Distance-based dot pattern (reviewed in Seger & Miller, 2010). A prototypical stimulus is selected (left), and category exemplars (right) are formed by randomly moving dots. (*c*) Groupings based on spatial frequency and orientation of Gabor patches (reviewed in Seger & Miller, 2010). Stimuli are formed by varying two dimensions: angle from vertical and width of the bars. Category is formed on the basis of the values of both dimensions and the diagonal line shows the boundary between A and non-A.

commonality, why are studies investigating learning of perceptual groupings and those investigating naïve beliefs included in large treatises on concepts such as Murphy's *Big Book of Concepts*? I think the major commonality is that both types of studies deal with different aspects of the same problem. The former studies try to understand how people acquire new categories, whereas the latter try to understand how people use and deploy existing concepts and conceptual networks in their thinking about the world.

Therefore, an important distinction to consider is between learning new categories and using existing categories. For example, a person may learn de novo that chimpanzees and orangutans are two different categories of great apes, or participants may come to a study equipped with this distinction and merely deploy their knowledge when categorizing great apes. Category knowledge is informative with respect to what people know, whereas category learning is informative with respect to what can be learned, how, and when. These types of conceptual behaviors prompt different developmental questions. Category learning prompts questions of how people acquire, store, and use categories across development, and whether the mechanisms of category learning change with development or remain the same. Category knowledge prompts questions of what children of different ages know in different knowledge domains, how this knowledge is organized, and what the sources of this knowledge are. Therefore, studying known categories versus category learning has led to somewhat different research traditions. At the same time, the latter question is a more basic one: Even if one studies existing knowledge in a particular knowledge-rich domain such as naïve biology or naïve physics, the question of how people acquired that knowledge in the first place needs to be answered. For example, in their book focusing on naïve biology, Inagaki and Hatano (2002, p. 1) give an example of biological reasoning by a 6-year-old girl:

Interviewer: What will happen to us if we eat nothing every day?
Child: We'll die.
Interviewer: Why?
Child: Cause we'll have no nutriments [*sic*].

It is clear that this reasoning involves much conceptual knowledge, including such categories as *life*, *death*, and *nutri[m]ent*. Do children learn these categories spontaneously, the way they learn some perceptual categories? Or does learning of these categories involve formal education or social interaction such as conversations with adults, reading, or watching educational media? Although we do not have definite answers to these questions, this chapter presents an argument that such categories are not learned spontaneously.

## Perceptual Groupings, Categories, Concepts, and Conceptual Networks

It is important to note that conceptual behaviors vary in levels of complexity ranging from simple perceptual groupings to arbitrary categories, to full-blown lexicalized concepts that are linked to other concepts that thereby form conceptual networks. The study of each type of conceptual behavior requires somewhat different research paradigms.

First, people can learn perceptual groupings or equivalence classes that are based on purely perceptual properties (examples of perceptual groupings are presented in Figure 12.1). Such groupings may include imposing categorical boundaries on sensory continua (known as categorical perception, e.g., Eimas, 1994), learning dot patterns coming from a single prototype and generalizing learning to distortions from the studied prototype, or forming a category based on image properties (see Bhatt & Quinn, 2010, for a review). Such groupings are typically studied using the *generalization* paradigm, which is perhaps the simplest conceptual task. In this task, a participant first learns a single grouping (i.e., Category A) and then decides whether a new stimulus is a member of A. Therefore such a paradigm is sometimes referred to as an A versus non-A task. For example, a participant can be familiarized with cats and tested on cats versus dogs. As we discuss later, most infant studies examining category learning use this kind of task. This is the simplest form of categorization because it is possible to extend category membership on the basis of global familiarity. Therefore, if members of Category A share some features, a novel item would be judged a member of A to the extent that it has these features.

A more complicated variant of conceptual behavior requires one to learn two or more mutually exclusive categories (e.g., cats versus dogs) at the same time. This task is often referred to as A versus B categorization. The categories are mutually exclusive because there are no members common to A and B (i.e., $A \cap B = \emptyset$). This task is more difficult than A versus non-A because a decision of whether a novel item belongs to A or to B cannot be made on the basis of global familiarity (i.e., both A and of B are equally familiar). The studied categories can be based on multiple correlated features (e.g., birds have wings, feathers, and beaks, whereas fish have scales, fins, and gills), few features (e.g., squirrels have a long, fluffy tail, whereas hamsters have a small tail), or relations among features (e.g., rectangles can be grouped into tall if the aspect ratio is less than 1, and wide if the aspect ratio is more than 1). The categories may be also deterministic (such that there is a subset of features that is sufficient to predict category membership with a 100% accuracy) or probabilistic (such that any feature or a combination of features predicts category membership only with a degree of probability). The categorization decision requires some representation of both categories and calculation of diagnostic features, that is, the features that distinguish A from B. The most useful features are those that have the highest cue validity, that is, features that are present in all (or most) members of A and in none (or few) members of B. Therefore, at the very minimum, some processing of two category structures is required: The participant has to compute feature frequency within and across categories. This task has been used in some studies with infants and non-human animals, and in many category-learning studies with children and adults.

An even more complicated variant of conceptual behavior is the ability to lexicalize categories and use them in reasoning, inference, prediction, or judgment. Such lexicalized categories can be defined as concepts proper. Lexicalization is critical as it enables acquiring knowledge that may not be directly observable in a given situation (e.g., dogs are friendly pets, they like meat, and are taken to a vet for a physical exam). In other words, having a word for a category allows accumulation of knowledge from sources that are not based on direct observation of category members. These sources include conversations with others, reading, and formal education. Such concepts proper can be studied in a variety of tasks, including grouping of items, property listing, picture naming, and many others. A grouping task may require participants to put together items of the same kind (e.g., toys versus animals), whereas an attribute listing task may require a participant to list properties of categories (e.g., of cats, birds, or animals).

Finally, a conceptual network involves knowledge not only of concepts but also of relations among these concepts. Take, for example, Newton's second law ($F = ma$) that acceleration of a body is directly proportional to the net force acting on the body and inversely proportional to the mass of the body. Here, the concepts of mass, force, and acceleration are linked together in a conceptual network. Such networks can be organized in a variety of ways; for example, networks of naturally occurring categories often have hierarchical, or taxonomical, organization (e.g., greyhound → dog → mammal → animal → living thing). One way of detecting such hierarchies is a classification task in which a diverse set of items is partitioned into *N* mutually exclusive and exhaustive subsets. These subsets can then be further partitioned into smaller groups or combined into larger groups.

A conceptual hierarchy is a variant of an advanced conceptual organization, and it depends critically on mastering the relation of class inclusion. Class inclusion refers to a situation when a subset of items ($s_1$) is properly included in a larger set (S) so that ($s_1 \leq S$), as in German shepherds ($s_1$) are dogs (S), and the mastery of class inclusion is examined in class-inclusion tasks. Conceptual hierarchies are related to reasoning with quantifiers (i.e., *all* members of $s_1$ are members of S, whereas *some* members of S *are not* members of $s_1$). However, it is not known whether the mastering of class-inclusion relations is necessary for understanding of the meaning of quantifiers *some*, *all*, *none*, and *at least one*—something that Piaget believed (Inhelder & Piaget, 1964)—or, alternatively, whether acquisition of quantifiers bootstraps the development of class-inclusion relations necessary for forming conceptual hierarchies.

Although it is tempting to consider perceptual groupings, categories, concepts, and conceptual networks as qualitatively different conceptual behaviors, this chapter argues that this is not the case and that there is continuity among these instantiations of conceptual behavior. According to this view, human concepts develop from perceptual groupings (something that can be also achieved by certain nonmammalian species) to conceptual networks that are likely to be unique to humans. One important goal of this chapter is to elucidate such development.

### Different Kinds of Categories

Are all categories the same? The standard answer to this question is yes. Here is an example of this point expressed by Shipley (1993): "Three psychological properties appear to characterize categories: (1) they have labels that are used to identify objects, (2) they serve as the range of inductive inferences, and (3) their members are believed to share a 'deep' resemblance" (p. 266). However, as discussed later, nonhuman animals and prelinguistic infants can form perceptual categories (Lazareva & Wasserman, 2008; Quinn, 2002a). This fact suggests that labels are not a necessary component of categories. In addition, people (as well as nonhuman animals) can learn arbitrary memory-based categories (e.g., items in their living rooms), suggesting that "deep resemblance" is not necessary either. Therefore, the kinds of categories that people can and do learn is quite broad and may include different kinds.

Although there is little doubt that categories differ in content, the most interesting distinctions pertain to category structure. Structural differences identified by researchers include syntactic differences (nouns versus verbs; e.g., Gentner, 1981), ontological differences (natural kinds versus nominal kinds; e.g., Kripke, 1972), taxonomic differences (i.e., basic level versus superordinate level; e.g., Rosch & Mervis, 1975), differences in organizational principle (entity categories versus relational categories; e.g., Gentner & Kurtz, 2005), differences in concreteness (concrete versus abstract categories; e.g., Barsalou, 1999), differences in category coherence and confusability (e.g., Homa, Rhoades, & Chambliss, 1979; J. D. Smith & Minda, 2000; Rouder & Ratcliff, 2004), and some other distinctions.

Kloos and Sloutsky (2008) proposed another structural distinction, one that could form the basis for many of the preceding distinctions. They proposed the idea of statistical density, that is, a measure of category structure that (a) can (in principle) be measured independently rather than be inferred from participants' patterns of response and (b) provides a continuous measure rather than a dichotomous one (which makes it well suited for capturing the graded nature of differences between categories).

Conceptually, statistical density is a ratio of variance relevant for category membership to the total variance across members and nonmembers of the category. Intuitively, statistical density is a measure of how members of a category are separated from nonmembers. A brief overview of statistical density ways of calculating it is presented here; a more detailed discussion is presented elsewhere (Kloos & Sloutsky, 2008). Three aspects of stimuli are important for calculating statistical density: variation in stimulus dimensions, variation in relations among dimensions, and attentional weights of stimulus dimensions.

First, a stimulus dimension may vary either within a category (e.g., members of a target category are either black or white) or between categories (e.g., all members of a target category are black, whereas all members of a contrasting category are white). Within-category variance decreases density, whereas between-category variance increases density.

Second, dimensions of variation may be related (e.g., all items are black circles), or they may vary independently of each other (e.g., items can be black circles, black squares, white circles, or white squares). Covarying dimensions result in smaller variability (and thus in greater density) than dimensions that vary independently.

The third aspect is the attentional-weight parameter. Without this parameter, it would be impossible to account for learning of some categories. In particular, when a

category is dense (i.e., when multiple dimensions are correlated within a category) even relatively small attentional weights of individual dimensions add up across many dimensions. This makes it possible to learn the category without supervision, and without attention to a particular dimension. Conversely, when a category is sparse, only few dimensions are relevant (e.g., members of a category are all red, but vary on multiple dimensions, such as shape, color, texture, and size). If attentional weights of each dimension are too small, supervision could be needed to direct attention to these relevant dimensions.

The idea of statistical density has important implications for the development of category learning. One possibility is that category learning progresses from spontaneous learning of highly dense categories to less spontaneous (and more guided or supervised) learning of more sparse categories.

### Spontaneous Versus Supervised Category Learning

Although it is difficult to precisely calculate the density of many categories surrounding young infants, some estimates can be made. It seems that many of these categories, while exhibiting within-category variability in color (and sometimes in size), have similar within-category shape, material, and texture (*ball*, *cup*, *bottle*, *shoe*, *book*, or *apple* are good examples of such categories); these categories should be relatively dense. As shown by Kloos and Sloutsky (2008), dense categories can be learned spontaneously, without supervision. Theoretically, category learning is considered *supervised* when (a) categories are marked or labeled and (b) participants are given feedback when they assign items to categories. In contrast, category learning is considered *unsupervised* when participants are only presented with items, without classes being labeled or feedback being provided.

The finding that dense categories can be learned without supervision has an important implication: prelinguistic infants should be able to implicitly learn many categories by interacting with the world surrounding them. Incidentally, the very first nouns that infants learn denote these dense categories (see Dale & Fenson, 1996; K. Nelson, 1974). Therefore, it is quite possible that some of early word learning consists of learning lexical entries for already known dense categories.

At the same time, many other concepts that are based on sparse categories (these include multiple legal, ethical, mathematical, and scientific concepts) are unlikely to be learned spontaneously. Learning of these concepts requires various degrees of supervision, and it is likely that many of these concepts are learned in the course of formal schooling. An interesting case is a set of naïve scientific concepts (e.g., naïve biology) that are naïve conceptual networks in domains studied by science (e.g., Hatano & Inagaki, 1994). Although there is little doubt that even preschoolers have some of these naïve concepts (e.g., the concept of a living thing), the origin of these concepts is not well understood. Are these concepts acquired spontaneously through experience with various kinds of plants and animals? Or are these concepts learned in a supervised manner, with supervision being offered by parents, children's books, television, and perhaps some other sources? Presently, we do not have definitive answers to these questions, but it seems highly unlikely that categories of such low statistical density are acquired spontaneously, without supervision (see Opfer & Siegler, 2004).

### Summary

This section reviewed the multiplicity of conceptual behaviors. It considered distinctions (a) between category learning and category use, (b) among different types of conceptual behaviors (e.g., perceptual groupings, categories, and concepts), and (c) among different kinds of category structures, as well as the ways these structures can be learned. In the sections to follow I review neural mechanisms of categorization, basic categorization abilities in nonhuman species, category learning in infancy, and lexical and semantic development.

## NEURAL BASES OF CONCEPTUAL BEHAVIORS

As discussed previously, conceptual behavior includes the ability to learn new categories as well as the ability to use already known ones. Therefore, there is little surprise that different brain structures subserve each. The first set of brain structures may come online earlier in development and enable the learning of categories that are represented in the second set of structures. In what follows, I review both types of brain structures. To foreshadow, some neural structures subserve both kinds of conceptual behavior, whereas other are unique for a given conceptual behavior.

### Neural Bases of Category Learning

Given the long evolutionary history of categorization and the multiplicity of behaviors described as "categorization,"

there is little surprise that categorization is subserved by multiple neural systems (e.g., Seger & Miller, 2010). When discussing brain mechanisms of category learning, researchers typically focus on the neocortex (visual cortex, the prefrontal and parietal cortices), the basal ganglia, and the medial temporal lobe.

The neuroscience of categorization has generated a substantial body of research (see Ashby & Maddox, 2005; Seger, 2008; Seger & Miller, 2010, for reviews). Advances in that field suggest that there might be multiple systems of category learning (e.g., Ashby, Alfonso-Reese, Turken, & Waldron, 1998; Cincotta & Seger, 2007; Nomura & Reber, 2008; Seger, 2008; Seger & Cincotta, 2002) and an analysis of these systems may elucidate how category structure interacts with category learning. Although the anatomical localization and the involvement of specific circuits remain a matter of considerable debate, there is substantial agreement that "holistic" or "similarity-based" categories (which are typically statistically dense) and "dimensional" or "rule-based" categories (which are typically statistically sparse) could be learned by different systems in the brain.

There are several specific proposals identifying brain structures that comprise each system of category learning (see Ashby & Maddox, 2005; Seger & Miller, 2010, for reviews). Most of the proposals involve three major hierarchical structures: cortex, basal ganglia, and thalamus. There is also evidence for the involvement of the medial temporal lobe (MTL) in category learning (e.g., Nomura & Reber, 2008; see also Love & Gureckis, 2007).

One influential proposal (e.g., Ashby et al., 1998) posited two cortical-striatal-pallidal-thalamic-cortical loops, which define two circuits that act in parallel. The circuit responsible for learning of similarity-based categories originates in extrastriate visual areas of the cortex (such as the inferotemporal cortex) and includes the posterior body and tail of the caudate nucleus. In contrast, the circuit responsible for the learning of rule-based categories originates in the prefrontal and anterior cingulated cortices and includes the head of the caudate (Lombardi et al., 1999; Rao et al., 1997; R. D. Rogers, Andrews, Grasby, Brooks, & Robbins, 2000).

In a similar vein, Seger and Cincotta (2002) distinguished between the *visual* loop, which originates in the inferior temporal areas and passes through the tail of the caudate nucleus in the striatum, and the *cognitive* loop, which passes through the prefrontal cortex and the head of the caudate nucleus. The visual loop has been shown to be involved in visual pattern discrimination in nonhuman animals (Buffalo et al., 1999; Fernandez-Ruiz, Wang, Aigner, & Mishkin, 2001; Teng, Stefanacci, Squire, & Zola, 2000), and Seger and Cincotta (2002) have proposed that this loop may subserve learning of similarity-based visual categories. The cognitive loop has been shown to be involved in learning of rule-based categories (e.g., Rao et al., 1997; Seger & Cincotta, 2002; see also Seger, 2008).

It is possible that category learning is achieved differently in the two systems (see Sloutsky, 2010). The critical property of the visual system is the reduction of information or *compression*, with multiple features frequently occurring in category exemplars being encoded. This compression can be achieved by many-to-one projections of the visual cortical neurons in the inferotemporal cortex onto the neurons of the tail of the caudate (Bar-Gad, Morris, & Bergman, 2003; Wilson, 1995). In other words, many cortical neurons converge on an individual caudate neuron. As a result of this convergence, information is compressed to a more basic form, with redundant and highly probable features being encoded (and thus learned) and idiosyncratic and rare features being filtered out.

Category learning in this system results in a reduced (or compressed) yet fundamentally perceptual representation of stimuli. Because compression does not require selectivity, compression-based learning could be achieved implicitly, without supervision, and it should be particularly successful in learning of dense categories.

The critical aspect of the second system of category learning is the cognitive loop which involves (in addition to the striatum) the dorsolateral prefrontal cortex and the anterior cingulate cortex (ACC), which is the cortical area subserving attentional selectivity and working memory. Given the importance of selective attention within this system, I will refer to this system as *selection based*. It enables attentional learning, that is, allocating attention to some stimulus dimensions and ignoring others (e.g., Kruschke, 1992, 2001; Mackintosh, 1975; Nosofsky, 1986). Unlike the compression-based system where learning is driven by reduction and filtering of idiosyncratic features (while retaining features and feature correlations that recur across instances), learning in the selection-based system could be driven by error reduction. As a result of learning, attention is shifted to those dimensions that predict error reduction and away from those that do not (e.g., Kruschke, 2001, but see Blair, Watson, & Meier, 2009 for evidence that regularity rather than error reduction may drive attention shifting). Given that attention has to be shifted to a

relevant dimension, the task of category learning within the selection-based system should be easier when there are fewer relevant dimensions (see Kruschke, 1993, 2001, for related arguments).

The selection-based system depends critically on prefrontal circuits because these circuits enable the selection of a relevant stimulus dimension and the inhibition of irrelevant dimensions. The selected (and perhaps amplified) dimensions are likely to survive the compression in the striatum, whereas the nonselected (and perhaps weakened) dimensions may not. There is thus little surprise that infants and young children (whose selection-based system is presumably still immature) tend to exhibit more successful categorization performance when categories are based on multiple dimensions than when they are based on a single dimension (e.g., Kloos & Sloutsky, 2008; Sloutsky & Robinson, 2013; L. B. Smith, 1989).

The idea of multiple systems of category learning has been supported by fMRI, neuropsychological, and behavioral evidence. In one neuroimaging study reported by Nomura and Reber (2008), participants were scanned while learning two categories of sine wave gratings. The gratings varied on two dimensions: spatial frequency and orientation of the lines. In the rule-based condition, category membership was defined only by the spatial frequency of the lines (similar to those depicted in Figure 12.1c), whereas in the holistic condition, both frequency and orientation determined category membership. Rule-based categorization showed greater differential activation in the hippocampus, the ACC, and medial frontal gyrus, while the holistic categorization exhibited greater differential activation in the head and tail of the caudate.

Another source of evidence is neuropsychological research. One of the most frequently studied populations is patients with Parkinson's disease (PD), because the disease often affects frontal cortical areas in addition to striatal areas (e.g., van Domburg & ten Donkelaar, 1991). As a result, these patients often exhibit impairments in both the compression-based and the selection-based systems of category learning. This group thus provides only indirect rather than clear-cut evidence for the dissociation between the systems.

For example, PD patients had difficulty learning probabilistic categories that were determined by the co-occurrence of multiple perceptual cues (Knowlton, Mangels, & Squire, 1996), a finding that suggests an impairment of the compression-based system. Impairments of the selection-based learning system have been demonstrated in patients with damage to the prefrontal cortex (which also often include PD patients). Specifically, multiple studies using the Wisconsin Card Sorting Test (Berg, 1948; Brown & Marsden, 1990; Cools, van den Bercken, Horstink, van Spaendonck, & Berger, 1984), have shown that patients often exhibit impaired learning of categories based on verbal rules, impairments in shifting attention from successfully learned rules to new rules, and impairments in shifting attention to formerly irrelevant dimensions (see Ashby et al., 1998, for a review). These patients thus exhibit multiple impairments of the selection-based system.

In sum, there is evidence that the compression-based and the selection-based system may be dissociated in the brain. Furthermore, although both systems involve parts of the striatum, they differ with respect to other areas of the brain. Whereas the selection-based system relies critically on the prefrontal cortex and the ACC, the compression-based system relies on inferotemporal cortex. As discussed in the next section, the inferotemporal and the prefrontal cortices may exhibit differential maturational time courses. The relative immaturity of prefrontal cortices and the MTL early in development coupled with a relative maturity of the inferotemporal cortex and the striatum should result in young children having a more mature compression-based than selection-based system, thus allowing them to be more efficient in learning dense than sparse categories (see J. D. Smith & Kemler-Nelson, 1984; L. B. Smith, 1989).

### Differential Maturational Course of Brain Systems Underlying Category Learning

Category learning is subserved by multiple brain areas that come online at different times. Studies of normal brain maturation (Caviness, Kennedy, Richelme, Rademacher, & Filipek, 1996; Giedd et al., 1996; Pfefferbaum et al., 1994; Sowell, Thompson, Holmes, Batth, et al., 1999a; Sowell, Thompson, Holmes, Jernigan, & Toga, 1999b) have indicated that morphology of some of the brain areas continues to change well into adulthood. As noted by Sowell, Thompson, Holmes, Batth, et al. (1999a), maturation progresses in a programmed way, with phylogenetically more primitive regions of the brain (e.g., brain stem and cerebellum) maturing earlier and more advanced regions of the brain (e.g., the association circuits of the frontal lobes) maturing later. In addition to the study of brain development focused on the anatomy, physiology, and chemistry of the changing brain,

researchers have also studied the development of function that is subserved by particular brain areas.

### *Maturation of the Inferotemoral (IT) Cortex*

Maturation of the IT cortex has been extensively studied in monkeys using single cell recording techniques. As demonstrated by several researchers (Rodman, 1994; Rodman, Skelly, & Gross, 1991), many fundamental properties of IT cortex emerge early. Most importantly, as early as 6 weeks, neurons in this cortical area exhibit adult-like patterns of responsiveness. In particular, Rodman et al. (1991) presented monkeys with different images (e.g., monkey faces and objects varying in spatial frequency), while recording electrical activity of IT neurons. They found that in both infant and adult monkeys, IT neurons exhibited a pronounced form of tuning, with different neurons responding selectively to different types of stimuli. These and similar findings suggested that the basic components of the IT circuitry develop relatively early (although some components may exhibit a more prolonged development). These findings contrast sharply with findings indicating a lengthy developmental time course of prefrontal cortices (e.g., Bunge & Zelazo, 2006).

### *Maturation of the Medial Temporal Lobe (MTL)*

Most empirical work examining maturation of the MTL consists of (a) analysis of behavioral performance on a set of marker tasks by human infants and children and (b) brain studies with monkeys and rodents. The anatomical data reviewed by Alvarado and Bachevalier (2000) suggest that while the basic pattern of connections between the hippocampal formation and the medial temporal cortical areas is established quite early in development, these connections are neither complete nor fully mature. In particular, maturation (as indexed by synaptogenesis and myelination) in the monkey hippocampus continues throughout the first postnatal year. Other postnatal maturational events include neurogenesis in the dentate gyrus and the strengthening of existing and development of new permanent connections between the hippocampus and surrounding cortices. Although it is not known when the perirhinal, entorhinal, and parahippocampal cortical areas of the MTL achieve functional maturity, these structures continue to show maturational changes across the first 2 years of life in the monkey. Therefore, it is likely that these areas continue to mature in humans at least through the preschool years (see C. A. Nelson, 1995).

In terms of behavioral evidence, competence on some of the tasks that are subserved by the MTL exhibits a very early onset, whereas competence on other tasks is not achieved until at least 5 years of age (e.g., Alvarado & Bachevalier, 2000; Hayne, 2004; Richmond & C. A. Nelson, 2007). In particular, novelty preference—often measured by pairing a familiarized and a novel item—exhibits early functional maturity, reaching adult-like levels around 8 months of age (Richmond & Nelson, 2007). In contrast, performance on relational memory tasks develops throughout the preschool years (e.g., Rudy, Keith, & Georgen, 1993; Sluzenski, Newcombe, & Kovacs, 2006; Yim, Dennis, & Sloutsky, 2013).

### *Maturation of the Prefrontal Cortex (PFC)*

There is a wide range of anatomical, neuroimaging, neurophysiological, and neurochemical evidence indicating that the development of the PFC continues well into adolescence (e.g., Sowell, Thompson, Holmes, Jernigan, et al., 1999b; see also M. C. Davidson et al., 2006; Luciana & Nelson, 1998; and Rueda et al., 2004 for extensive reviews).

The maturational course of the PFC has been studied in conjunction with research on executive function—the cognitive function that depends critically on the maturity of the PFC (Davidson, Amso, Anderson, & Diamond, 2006; Diamond & Goldman-Rakic, 1989; Fan, McCandliss, Sommer, Raz, & Posner, 2002; Posner & Petersen, 1990). Executive function comprises a cluster of abilities such as holding information in mind while performing a task, switching between tasks or between different demands of the same task, inhibiting a dominant response, deliberate selection of some information and ignoring other information, selection among different responses, and resolving conflicts between competing stimulus properties and competing responses.

There is a large body of behavioral evidence that early in development children exhibit difficulties in deliberately focusing on relevant stimuli, inhibiting irrelevant stimuli, and switching attention between stimuli or stimulus dimensions (Diamond, 2002; Hanania & L. B. Smith, 2009; Kirkham, Cruess, & Diamond, 2003; Plude, Enns, & Brodeur, 1994; Zelazo et al., 2003).

Maturation of the prefrontal structures in the course of individual development is associated with progressively greater efficiency of executive function (Nagy, Westerberg, & Klingberg, 2004) potentially affecting the ability to deliberately focus on what is relevant while ignoring what is irrelevant. This is a critical step in acquiring the ability to form abstract, similarity-free representations of categories and use these representations in both category and property induction. Therefore, the development of relatively abstract category-based generalization may hinge on the

development of executive function. As suggested earlier, while the selection-based system could be deployed by default in adults when learning is supervised (e.g., F. G. Ashby et al., 1998), it could be that early in development, it is the compression-based system that is deployed by default.

Taken together, these findings suggest that the cortical structures that subserve the compression-based learning system (i.e., IT) come online earlier than the cortical circuits that subserve the selection-based learning system (i.e., PFC). This asynchronous maturational time course may provide an explanation of why early in development children learn dense, similarity-bound categories with ease and efficiency (as these could be efficiently learned by the compression-based system), while often struggling to learn sparse, similarity-free ones (as these require the involvement of the selection-based system).

In sum, some brain structures underlying category learning exhibit early maturity, whereas others undergo protracted development. As a result, the compression-based system exhibits early onset, whereas the selection-based system is a product of protracted development. These developmental asynchronies suggest an important candidate principle of the development of category learning: The compression-based system may be evolutionary more primitive, whereas the selection-based system is evolutionary late (see J. D. Smith et al., 2012, for cross-species analyses).

### Neural Bases of Conceptual Processing

The study of the neural basis of conceptual processing has been linked to the study of semantic memory, that is, a division of declarative memory that includes knowledge of the meaning of objects and words. There are several comprehensive reviews of the neural basis of semantic memory (Humphreys & Forde, 2001; Mahon & Caramazza, 2009; Martin, 2007; Tranel, Damasio, & Damasio, 1997), most of which are focused on representation of object concepts. Most of the reviews suggest that semantic memory involves a complex network, such that object properties are stored throughout the brain with specific sensory and motor-based information stored in their corresponding sensory and motor areas.

There is a large body of converging fMRI and neuropsychological evidence implicating the temporal lobes (particularly the posterior region of the left temporal lobe) in storing semantic information about concrete objects (see Martin, 2007, for a comprehensive review). One particular area that transpires in studies of conceptual processing and semantic memory is the fusiform gyrus. In a set of studies using the repetition suppression paradigm (i.e., attenuation of a neural response to repeating stimuli), it was found that the left fusiform gyrus exhibits an attenuated response not only to previously seen objects, but also to different items drawn from the same basic-level category (Koutstaal, Wagner, Rotte, Maril, & Buckner, 2001; Simons, Koutstaal, Prince, & Wagner, 2003). In contrast, the right fusiform gyrus exhibited repetition suppression only to identical objects (see Martin, 2007, for a discussion). Other regions, such as the PFC, may also be prominently involved, especially when retrieving information about the objects.

There is a dearth of studies examining the development of the brain structures subserving semantic memory (although there is much research on involution and decay of semantic memory due to neurodegenerative diseases or aging). First, because semantic memory deals with organized knowledge about the world and is tied to language, it is difficult to design an adequate animal model of semantic memory. In the absence of an animal model, the study of neurodevelopment is exceedingly complicated. And second, it is possible that the development consists in forming connections between areas subserving semantic memory rather than of maturation of constituent circuits. If this is the case, semantic memory may exhibit protracted development.

### Summary

Conceptual behaviors are subserved by multiple brain areas. First, there is the distinction between areas subserving category learning and areas subserving storage of known categories. Second, it is possible that there are multiple brain systems subserving category learning, including an evolutionarily more primitive and a more recent one. Given that some forms of conceptual behavior are evolutionarily old, it is not surprising that nonhuman animals exhibit evidence of conceptual behavior. The next section reviews this evidence.

## CATEGORIZATION IN NONHUMAN ANIMALS

In their seminal work on conceptual development *The Early Growth of Logic in the Child: Classification and Seriation*, Inhelder and Piaget (1964) considered a number of possible hypotheses regarding the source of conceptual

development. One such hypothesis is that conceptual development is a result of language development. This hypothesis is plausible given that language carries many conceptual distinctions. Although Piaget and Inhelder rejected this hypothesis, they did so without sufficient evidence. That is, they relied primarily on the fact that deaf children exhibit the ability to classify, but, given that deaf children are also able to use language (even if it is a different modality), this is a weak argument. Today, we can reject a strong form of hypothesis (i.e., that language development is the primary contributor to conceptual development) on much firmer grounds: There is much evidence for conceptual behavior in nonlinguistic organisms (such as nonhuman animals and prelinguistic human infants).

Herrnstein and Loveland (1964) were among the first to present evidence of category learning in nonhumans: They successfully trained pigeons to discriminate photographs that contained a person from photographs that did not. Subsequent studies successfully expanded training to a variety of natural categories, including fish and trees among others (see Lazareva & Wasserman, 2008, for a review). Wasserman and colleagues (Bhatt, Wasserman, Reynolds, & Knauss, 1988) trained pigeons with four categories, such that cat, flower, car, and chair elicited a different response (i.e., pecking of a different key). Although pigeons exhibited robust learning, there was a substantial generalization decrement such that their accuracy dropped when they were presented with novel stimuli from the studied categories. In addition, performance on stimuli that were frequently repeated during training was higher than on stimuli that were repeated only once. These data indicated that pigeons might be relying on memory for items in their categorization behavior.

While memory for individual items is a potential source of category learning in pigeons, image statistics could be another source. Watanabe and colleagues (Watanabe, Sakamoto, & Wakita, 1995) trained pigeons to differentially respond to paintings by Monet and Picasso. Following training, pigeons successfully generalized to black-and-white versions of the paintings that had been trained as well as to novel paintings created by the studied artists.

Cook, Katz, and Cavoto (1997) and Wasserman and colleagues (Young & Wasserman, 1997, 2001) demonstrated that pigeons were able to use relatively abstract categories of "same" versus "different." Pigeons were presented with either homogenous or heterogeneous displays similar to those presented in Figure 12.2. Pigeons successfully learned to classify different types of displays as "same" (i.e., homogeneous displays) or "different"

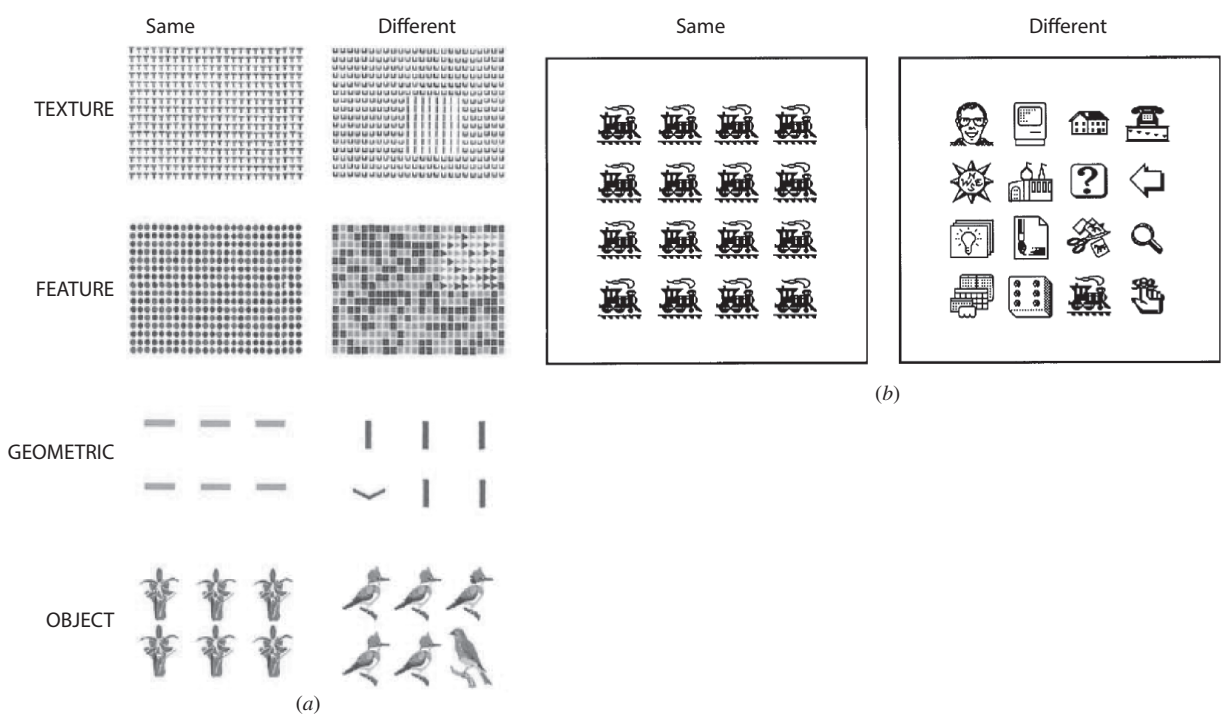


**Figure 12.2** (*a*) Stimuli used in Cook et al. (1997). (*b*) Stimuli used in Young and Wasserman (2001).

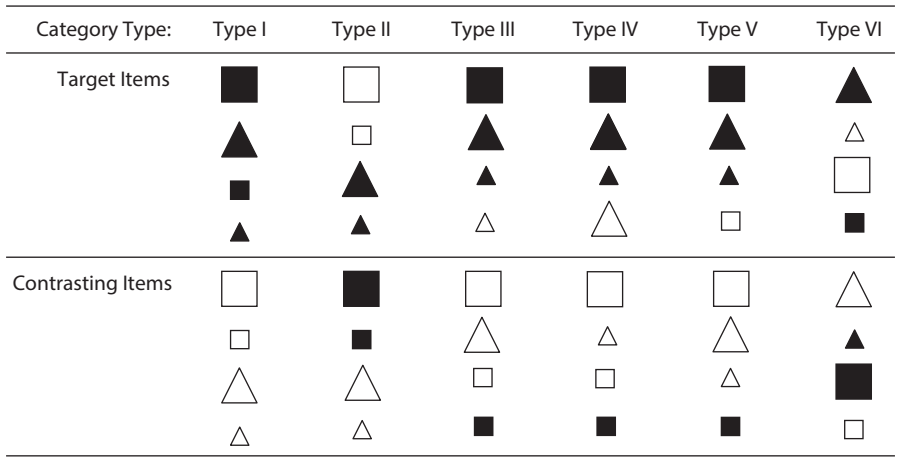


**Figure 12.3** Six types of category structure used in Shepard et al. (1961).

(i.e., heterogeneous) displays. Although it is tempting to conclude that pigeons learned a highly abstract category, Young and Wasserman presented persuasive arguments that pigeon behavior is likely to be controlled by purely visual characteristics of the displays (e.g., the amount of variability or entropy). In this case, learning might have involved categorizing zero-entropy (i.e., no variability displays) from nonzero entropy.

J. D. Smith, Minda, and Washburn (2004) examined category learning in monkeys. Monkeys learned one of the six category types used in an influential study by Shepard, Hovland, and Jenkins (1961). As shown in Figure 12.3, category types I 0and II are based on a rule (Category I is the simplest case as the rule is white objects in Category A and black objects on Category B), whereas type VI category requires memorization of each category member. Shepard et al. (1961) used these categories in a category learning task and demonstrated that there is a gradient of difficulty in learning these categories: People easily learn type I category, type II is more difficult, types III–V are even more difficult, and type VI is the most difficult. However, J. D. Smith et al. (2004) presented these categories to monkeys and found that although type VI category was somewhat more difficult, the difference was substantially smaller than in humans. Therefore, even monkeys are likely to rely on rote memory of items when learning categories. In addition, monkeys were less likely than humans to rely on rules when learning category types I and II.

Vice versa

As suggested previously, it is possible that the compression-based category learning—learning that is based on multiple correlated features—is a more evolutionary primitive than learning of categories based on a single feature. This point is illustrated in a visual category learning in rhesus monkeys (Vogels, 1999). The monkeys ably learned to distinguish complex color images of trees from other objects and generalized from old to novel exemplars. It was also found that categorization was not based on a single feature such as shape, color, or texture. None of the features alone was sufficient to produce generalization. Instead, generalization was based on a combination of multiple features.

### Summary

The reviewed findings indicate that category learning is not an exclusively human ability, learning of many categories may be achieved by the perceptual system and it does not require language. At the same time, the limits of the nonlinguistic category learning are not known: Researchers have yet to discover which category structures cannot be learned by nonlinguistic organisms, even when learning is supervised. The critical issue here is not to find such categories: There is little doubt that there are many categories that cannot be learned by nonhuman animals (e.g., odd versus even numbers). Instead the goal is to understand what makes the underlying structures critically dependent on language.

## CONCEPTUAL DEVELOPMENT IN INFANCY

If forced to reduce conceptual behaviors in infancy to two primary findings, I would list (1) the ability of preverbal infants to learn categories at all and (2) the ability to learn many of these categories without a teaching (or supervisory) signal. These and other issues are discussed in the following sections.

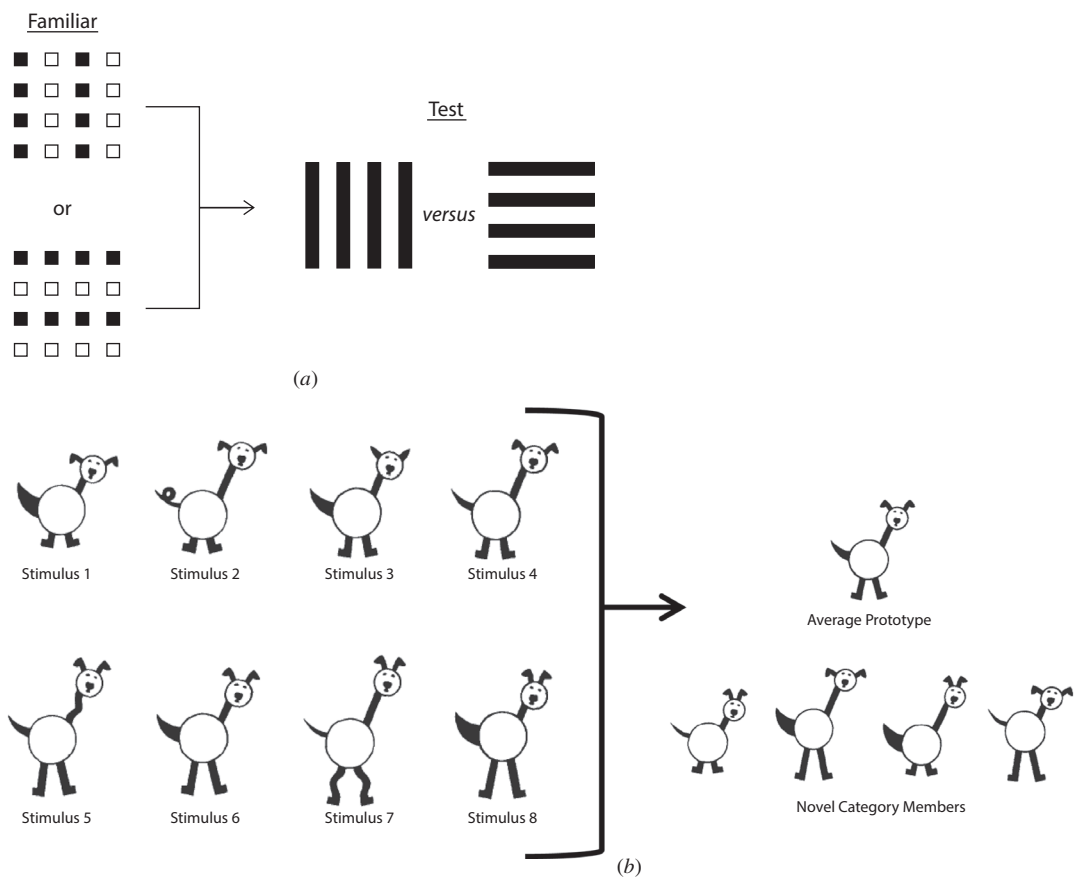


**Figure 12.4** Example of luminance-based categories used in the Quinn, Eimas, and Rosenkrantz (1993) study (*a*) and of creature-like categories used in the Younger (1990) study (*b*).

### Preverbal Infants Exhibit Evidence of Category Learning

How does one examine conceptual behaviors in a nonlinguistic organism that cooperates for only a short period of time? This is not an easy task. Researchers in animal learning typically use a generalized response paradigm. In this paradigm an organism is trained to respond differently to stimuli from Set A and Set B and is then presented with a novel stimulus from either of the two sets. Category learning is inferred from a set-appropriate response, provided that there is also evidence that the novel stimulus was discriminated from the one that had been studied earlier. Infant studies are generally based on the same logic, but because infants' period of cooperation is very short, animal paradigms cannot be applied directly.

Category learning in human infants is typically examined using a wide range of stimuli and a wide range of research paradigms. Stimuli used with infants typically employ sensory-defined categories, pictures of animal-like creatures (e.g., see Figure 12.4) and real objects. Research methods include visual attention, object examination, sequential touching, and operant conditioning paradigms. In visual attention paradigms, participants are first familiarized with (or habituated to) members of a to-be-learned category. They are then presented with either a novel item from the studied category or an item from a nonstudied category. Learning is inferred if the infant displays (a) longer looking to an item from a nonstudied category coupled with (b) the ability to discriminate familiar from novel members of the studied category. Object examination and sequential touching paradigms (Rakison & Butterworth, 1998; see Cohen & Cashon, 2006, for a review) are based on a similar logic, but participants are presented with toy replicas of objects and given an opportunity to examine these replicas. "Examining" is often defined as focused looking in the presence or absence of manipulation (Cohen & Cashon, 2006).

In the sequential touching paradigm, the infant is presented with replicas of objects from two categories

(e.g., horses and cows) and is given an opportunity to examine these objects. The sequential order in which the infant examines the objects serves as the dependent variable. Any deviation from randomness (i.e., greater probability of examining objects within a category than across categories) is taken as evidence that the infant is responding on the basis of the category.

Two important findings stem from research using these paradigms. First, pioneering studies using visual attention paradigms by Eimas, Cohen, and their colleagues have shown that, at least by about 10 months of age (and often as early as by 3 months of age), infants can learn various animal categories (Eimas & Quinn, 1994; Oakes, Coppage, & Dingel, 1997; Quinn et al., 1993), as well as more artificial categories of patterns of luminance (Bhatt & Quinn, 2010, for a review), geometric shapes (Bomba & Siqueland, 1983; Quinn, 1987), schematic animals (Younger, 1990; Younger & Cohen, 1985), and schematic faces (Strauss, 1979).

And second, *what* babies learn depends on the input. For example, Quinn and colleagues (e.g., Quinn et al., 1993) found important asymmetries in category learning (perhaps the most striking one is that babies often learn categories of cats that exclude dogs, but not of dogs that exclude cats). This finding is important because it clearly indicates that infants are sensitive to category structure. While making a significant step of demonstrating infants' sensitivity to structure, the study did not reveal which aspects of the structure infants are sensitive to. Subsequent work (French, Mareschal, Mermillod, & Quinn, 2004) provided answers to this question. French et al. (2004) found that what infants learn is affected by variability in the input: Greater featural variability in the input is accompanied by learning of a broader category. In particular, cats' features tend to vary less than those of dogs (see Figure 12.5). As a result, when presented with cats, babies tended to learn a narrow category of cats, whereas when presented with dogs, babies tended to learn a broader category of cats-and-dogs. These findings were corroborated by subsequent experimental and computational work in which researchers created artificial sets of broadly varying cats and narrowly varying dogs, resulting in a reversal of the asymmetry (French et al., 2004).

Infants' sensitivity to input variability also transpired in an object examination task. For example, Oakes et al. (1997) found that 10-month-olds were more likely to dishabituate to a novel out-of-category item when the set of items used in the study was uniform than when it was variable. However, it was not clear from this study whether the more variable input resulted in a failure to learn or in learning a broader, more inclusive category.

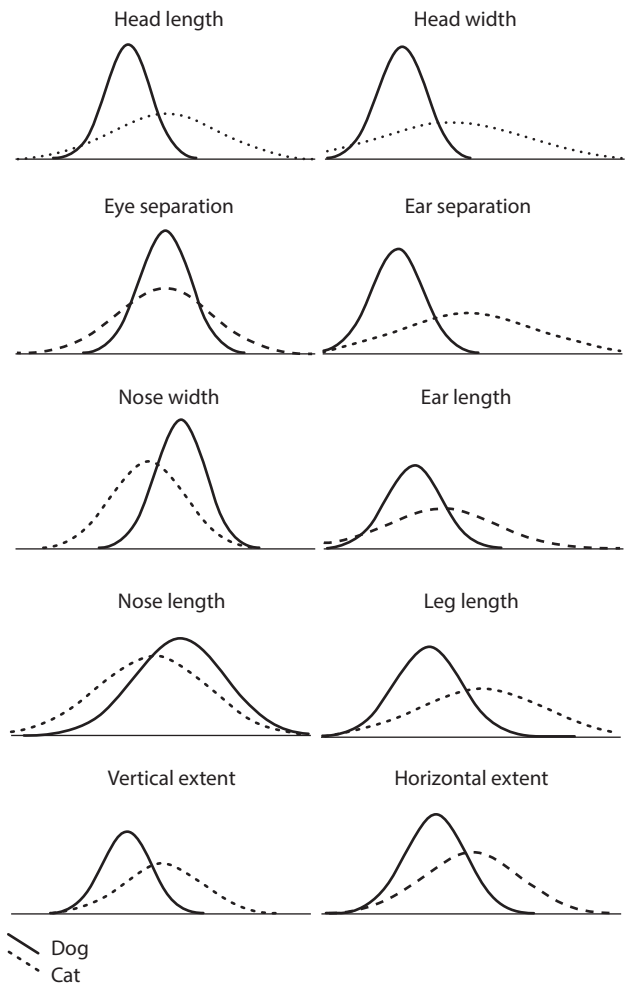


**Figure 12.5** Feature-value distribution in cats and dogs used in the French et al. (2004) study. The distribution of cats' features subsume those of dogs.

*Source*: French et al., 2004.

Although variability of input is important, it is not the only factor that affects infant category learning. For example, Gliozzi, Mayor, Hu, and Plunkett (2009) and Mather and Plunkett (2011) demonstrated both computationally and experimentally that even with the same set of items, the order in which items are presented affects what infants learn: In one condition, the order of presentation minimized the perceptual distance between consecutive exemplars, whereas in the other condition, the order of presentation maximized the distance between successive exemplars. Infants exhibited robust category learning only in the later, but not in the former condition. Given that in Mather and Plunkett's (2011) experiments only the order

of presentation of perceptual information differed across conditions, it is reasonable to conclude that perceptual categories are the starting point of conceptual development. However, as I discuss later, this conclusion is not uncontroversial: Some researchers believe that perceptual category learning has little, if anything, to do with conceptual development.

In sum, there is massive evidence that infants can learn categories and that the structure of input affects their learning. At the same time, little can be inferred from the studies reviewed earlier about how (and for how long) the learned categories are remembered. As noted by Hayne (1996), there is no evidence from visual attention and touching paradigms that infants retain the learned categories for longer than 15 seconds. Information about retention is provided by studies that use operant conditioning.

Perhaps the best-known operant conditioning task examining infants' category learning is the mobile conjugate reinforcement paradigm (see Hayne, 1996, for a review; see also Howe, Chapter 6, this *Handbook*, this volume). In this task, 2- to 6-month-old infants typically learn to produce movement in an overhead crib mobile by kicking (the mobile is connected via a ribbon to the infant's ankle). In this paradigm, the researcher first records each infant's baseline kicking, that is, the number of kicks that occur when the mobile is not attached to the ankle. The infant is then given a series of 15-minute training sessions with 24 hours between each. Each training session is divided into "training" and "testing" blocks. The training blocks include a reinforcement period (when the mobile is connected to the ankle) and a nonreinforcement period (when the mobile is not connected). During all sessions, the number of times per minute that an infant kicks when the ribbon is attached is recorded. A comparison of kicking rates during the nonreinforced testing and nonreinforced baseline provides a measure of learning, memory, and categorization (or generalization). Although this paradigm has been mostly used to study learning and memory (e.g., how much do infants remember after certain delays?), it also lends itself to the study of categorization. To use it for this purpose, the researchers follow the same logic as they do in other paradigms studying categorization. During training they present an infant with a number of different mobile exemplars and then test the infant with novel mobiles. Testing is introduced either immediately as in other paradigms or following a delay, which allows researchers to examine the retention of a learned category over time. The extension of the learned behavior to a novel mobile indicates that the infant learned the category of mobiles.

Results indicated that infants as young as 3 months old can learn the category and retain it for 24 hours, often for as long as about 5 days (Rovee-Collier, Greco-Vigorito, & Hayne, 1993). Therefore, if categorization is construed as generalization, these studies indicate that as early as 3 months, infants not only learn categories but also retain them for protracted periods.

In sum, as argued by Quinn (2002b), infants can do more than just detect and discriminate; they can also group and generalize stimuli in their environment, exhibiting evidence of conceptual behavior.

### Preverbal Infants Can Learn Categories Without Teaching or Supervisory Signal

As discussed earlier, one of the central findings of infancy research of the past 20 years is that infants can learn categories without a teaching (or supervisory) signal. Supervised and unsupervised learning may result in different representations of a category in neural networks (e.g., Japkowicz, 2001) and in human learners (e.g., Kloos & Sloutsky, 2008).

Most infancy studies use unsupervised learning: Infants are generally familiarized with category exemplars and then tested on either a new member of the studied category or on a novel item. The fact that infants exhibit preference for a novel item indicates that they can learn a category without supervision. It should be noted, however, that most studies demonstrating the ability of infants to learn categories familiarized infants with only a single category. Despite its many advantages, this paradigm has a number of limitations.

Most importantly, category learning is inferred from a preference for a novel item and, therefore, much depends on the choice of the novel item. In many situations, this state of affairs leads to the difficulty of interpreting what exactly was learned. For example, consider an experiment in which 10-month-olds are familiarized with balls varying in color and size and are tested on balls versus flowers. Further suppose that participants exhibit reliable novelty preference, looking longer at a flower than at a new ball. Although it is clear that participants learned something, what exactly they learned is less clear. Is it the category of balls, round things, things without parts, or things with uniform texture?

One way of dealing with this situation is to use natural kind categories at different levels of the taxonomy. For example, if a participant is familiarized with cats and prefers a novel horse to a novel cat, then the participant has learned the category of cats that excludes horses.

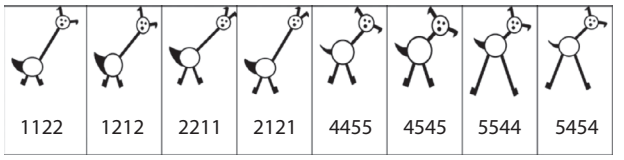


**Figure 12.6** Stimuli used in Plunkett et al. (2008).

However, with this paradigm researchers face another challenge: It is not known whether infants learn a new category or add novel items to an already existing category.

Another way of addressing this problem is to present infants with the task of learning two categories simultaneously. Although this approach has challenges and is still rarely used in the study of infant categorization, the few existing studies using this method have been encouraging. In one study, Plunkett, Hu, and Cohen (2008, Experiment 2) presented 10-month-olds with a stimulus set consisting of two categories (see Figure 12.6, for an example: The four items on the left are members of Category A and the four items on the right are members of Category B). Because items had continuous dimensions (e.g., neck length or ear separation), a test item could be either an extreme case of Category A (and thus far from Category B) or fall between Categories A and B. When presented with these item types, infants exhibited a preference for the in-between category items, thus suggesting that they had learned two categories.

The second example comes from a study by Sloutsky and Robinson (2013), who used a variant of "switch" task (Werker, Cohen, Lloyd, Casasola, & Stager, 1998). These researchers presented 14-month-olds with two categories, one defined by the same color and another defined by the same shape. Here, the two categories were presented in different contexts: Items from Category A were presented on one background, in a certain location on the screen, and with a particular kind of ornamentation (border) around them, whereas items from category B were presented on a different background, in a different location on the screen, and with a different ornamentation. At test, participants were presented with (a) same trials (new members of studied categories), (b) new trials (entirely new items), and (c) switch trials (new members of a studied category presented in the context of the other category). Learning was inferred when participants exhibited novelty preference on switch and new trials, but not on same trials. Participants indeed exhibited this pattern, indicating that they succeeded at learning both categories.

The third example comes from a study by McMurray and Aslin (2004), who introduced a two-alternative anticipatory eye-movement paradigm. In this paradigm, one category is associated with one outcome (e.g., an engaging object appearing on one side of the screen), and another category is associated with another outcome (i.e., another engaging object appearing on another side of the screen). Category learning is inferred from anticipatory looking to the correct side of the screen when a member of one of the two categories is presented. McMurray and Aslin (2004) reported successful learning of two categories by 5- and 7-month-old infants.

Note that in none of these paradigms were participants explicitly given a teaching signal or explicitly rewarded for a correct response. Therefore, taken together, these findings present strong evidence that a teaching signal is not necessary for category learning in infancy. These findings raise another important question: To what extent can infants benefit from supervision? I address this question in the section on the role of language in infant category learning.

## Controversial Issues in Infant Category Learning

Although the question of whether infants can learn categories is relatively uncontroversial—they do!—questions pertaining to how infants learn categories and how these categories relate to later conceptual development have generated considerable disagreement. These points of disagreement pertain to (a) the way infants learn and represent global categories; (b) whether category learning in infancy is a continuous or a discontinuous process, and (c) the role of language in infant category learning. Only some of these issues have been resolved to date.

### *The Nature of Global Categories in Infancy*

There is a large body of evidence that young infants can form basic-level categories such as cats or dogs and more global-level superordinate categories such as animals or vehicles. According to one view (Rosch et al., 1976), there is a developmental progression from mastering basic-level categories (e.g., cat or truck) to superordinate categories (e.g., animal or vehicle). The initial evidence for this view came from sorting experiments with children (Rosch et al., 1976, Experiment 8). Children were presented with triads of items such that the target and one test item were either (a) members of the same basic-level category (e.g., two dogs) or (b) members of the same superordinate category (e.g., a dog and a bird). For both types of triads, the third item came from a different superordinate category (e.g., a car). Children were asked to point to the two that are alike and that are the same kind of thing. Results were

unambiguous: 3-year-olds were at ceiling in matching basic-level categories (i.e., 99% correct) and at chance in matching superordinate categories (i.e., 55% correct). These and similar findings led to the conclusion that in the course of development basic-level categories are acquired prior to superordinate categories.

According to another view, the progression is in the opposite direction: More global superordinate categories are acquired prior to basic-level ones (Mandler & Bauer, 1988). Recall that Rosch et al. (1976) tested children (but not infants) and the primacy of the basic-level categorization was made by logical extension: If 3-year-olds have difficulty forming superordinate categories, how could younger children and infants form such categories? However, this logical extension may not be warranted. As argued by Mandler and Bauer (1988), "the developmental status of basic-level versus superordinate categories has not been systematically examined in children under 2 years of age" (p. 249). To address this issue and determine whether basic-level categories are in fact formed earlier than superordinate categories, Mandler and Bauer examined categorization in 1- to 2-year-olds, using an object manipulation task. In one experiment, for the basic-level categories participants were presented with various toy dogs and toy cars, whereas for the superordinate level participants were presented with various toy animals and toy vehicles. Categorization was inferred from participants' behavior in a sequential touching task—toddlers' tendency to touch objects belonging to the same category. The researchers found that even 12-month-olds ably distinguished the basic-level categories coming from different superordinate categories (e.g., dogs versus cars), whereas only 20-month-olds distinguished two superordinate categories (e.g., animals versus vehicles). Furthermore, even 20-month-olds failed to distinguish two basic-level categories that came from the same superordinate one (e.g., dogs versus horses). On the basis of these data, they thus suggested that more global categories appear earlier in development than basic-level categories.

Although the conclusion of the primacy of global categories is tempting, one should not forget that much younger infants (sometimes as young as 3 months of age) can learn basic-level categories drawn from the same superordinate category, such as cats versus dogs (Quinn et al., 1993). However, notice that Mandler and colleagues used manual exploration procedures, whereas Quinn et al. (1993) used visual attention procedures. Hence, depending on the learning procedure, infants may learn different types of categories—*perceptual* categories in the course of visual exploration, and *conceptual* categories in the course of visual and manual exploration. In addition, it is possible that basic-level categories can be learned perceptually whereas superordinate-level categories cannot (because the latter have too much perceptual variability to be picked up by the perceptual system). While this possibility is not unreasonable, it currently cannot account for a number of important findings.

Perhaps the most critical findings are that very young infants can, in fact, learn global-level categories by means of visual perception. For example, Behl-Chadha (1996) presented 3- to 4-month-olds with a variant of the visual familiarization task and found that infants successfully formed a global category of mammals that included novel mammals but excluded other nonmammalian animals such as birds and fish. Quinn and Johnson (2000) reported similar findings for 2-month-old infants. Critically, not only were young infants able to learn these global categories, but their ability to learn these categories appeared to come online before the ability to learn constituent basic-level categories. When Quinn and Johnson (2000) modeled these data using an auto-associator network (a simple network that learns to output the input or its part), the network also learned global categories before learning basic-level categories (see also T. T. Rogers & McClelland, 2004). These findings are important because the network had only perceptual input and yet was capable of learning global-level categories before learning basic-level categories. Taken together, results reviewed in this section strongly suggest that perceptual information in global-level categories is sufficient to allow very young infants and networks to learn these categories by perceptual means.

### *Continuity Versus Discontinuity (or Monism Versus Dualism) in Infant Category Learning*

The fact that infants can learn both basic-level and global-level categories generated another controversy. Some researchers (e.g., Mandler, 1992) suggested that categories learned by very young infants are perceptual in nature, whereas categories of older infants, children, and adults are conceptual in nature (i.e., are based on more abstract, nonperceptual features). According to this account, the latter categories have very little in common with the former categories. Other researchers (e.g., Eimas, 1994) rejected such dualism, suggesting instead that conceptual categories develop out of perceptual categories. As discussed in the following, there is substantial evidence generated by each account.

Although traditionally this controversy has been identified as continuity versus discontinuity issue in infant category learning (e.g., Eimas, 1994; Quinn, 2011), all those who participate in the debate appear to be committed to the idea of continuity. For example, Eimas rejected the idea of discontinuity in favor of more continuous development. He wrote, "Mandler (1992) has assumed that the earliest categorical structures of infants, the earliest parsing of things and events in the world, are perceptual in nature (cf. Quinn & Eimas, 1986) and remain so until they undergo a process of perceptual analysis that yields the meaningful conceptual representations of older children and adults—representations that permit us to know the kind of thing being represented" (1994, p. 85). However, his opponent Jean Mandler expressed similar commitment to continuity: "My ultimate goal is to develop such a theory and to show how the attributes of adult concepts can be derived from the primitives of infants" (1992, p. 587). Therefore, given that both sides endorsed continuity, I refer to this controversy as "monism versus dualism" in category learning. According to the dualist view, adult concepts can be derived from the primitives of infants, but to do so one has to abandon the view that infants engage only in sensory (or perceptual) categorization. The dualist position therefore postulates the existence of two separate processes in infant categorization, namely, perceptual and conceptual categorization. According to the monist view, concepts can and do arise from perceptual processing.

For example, Mandler (1992, 1999) offered a dualist account of category learning (but see Müller & Overton, 1998, for a review and critique of this approach). The central idea of this proposal is that true concepts cannot emerge from perceptual categories and must have conceptual primitives as their starting point. These conceptual primitives are a result of perceptual analysis, which is "a process in which a given perceptual array is attentively analyzed, and a new kind of information is abstracted. The information is new in the sense that a piece of perceptual information is recoded into a non-perceptual form that represents a meaning" (Mandler, 1992, p. 589). Representations that result from perceptual analysis are called image schemas. These image schemas (e.g., Self-Motion, Animate-Motion, Caused-Motion) can be derived from perceptual structure, but cannot be reduced to it. In turn, concepts, such as "animacy," "inanimacy," or "agency," are built from these conceptual primitives. Evidence supporting these ideas comes from a set of studies conducted by Mandler and her colleagues (Mandler & McDonough, 1996, 1998; McDonough & Mandler, 1998) in which 11- to 14-month-old infants generalized properties (e.g., drinking) to a broad category such as animals. Under the assumption that there is very little perceptual commonality among members of these global categories, it was concluded that these generalizations could be only made on the basis of conceptual information.

In opposition to this dualist approach, Eimas (1994) offered a monistic view according to which conceptual knowledge has its origins in perception. First, as discussed earlier, very young infants can acquire both basic-level and more global categories of natural kinds by perceptual means, and it is possible that development consists of quantitative enrichment and not a qualitative transformation of these early categorical representations. Second, in principle, perceptual and associative processes can result in more abstract representations. For example, biological motion (which is defined by perceptual input) may form the basis for a representation for animate beings. In other words, perceptual categories acquired very early in development may give rise to more abstract categories acquired later in development. In sum, according to this view, conceptual knowledge may develop from perceptual origins if development is considered a sequence of events rather than a two-step process. Although the controversy remains unresolved, each side of the debate has generated interesting research in support of its position.

### *The Role of Language in Infant Category Learning*

The third controversial issue is the role of language in early category learning. The issue is of critical importance because it has implications for understanding the role of language in cognitive development, the nature of early category learning, and the extent to which supervision may affect early category learning. Given that this controversy is not unique for conceptual development in infancy, I will return to it again later when reviewing conceptual development after infancy.

Some researchers suggest that from early in development, words are "names" of objects and categories (Balaban & Waxman, 1997; Waxman & Booth, 2002; Xu, 2002). At the computational level (Marr, 1982), this approach assumes that words function as supervisory signals directing and guiding learning. Thus, if two discriminable items share the same count noun (e.g., both are called "a dax"), the name serves as a top-down signal that the items are equivalent in some way (cf. Gliga, Volein, & Csibra, 2010). Similarly, if two items are labeled differently (e.g., "a dax" versus "a fep"), the names serve as a top-down signal that the items are different.

Another possibility is that early in development, words, just like any other perceptual feature, are first and foremost part of the input, and they influence categorization in a bottom-up, nonsupervisory fashion (Colunga & L. B. Smith, 2005; Plunkett et al., 2008; Sloutsky & Fisher, 2004a). Under some conditions, linguistic input may facilitate learning (Colunga & L. B. Smith, 2005; Plunkett et al., 2008; Samuelson & L. B. Smith, 1998, 1999), whereas under other conditions it may hinder learning (Plunkett et al., 2008; Robinson & Sloutsky, 2007a; 2007b; Sloutsky & Robinson, 2008). According to this view, even if words start out as part of the stimulus input, they may eventually become supervisory signals (Casasola & Bhagwat, 2007; Casasola, Bhagwat, & Burke, 2009; Gliozzi et al., 2009; Mayor & Plunkett, 2010; Sloutsky, 2010; L. B. Smith & Yu, 2008).

Each of these possibilities presumes a distinct mechanism and neural architecture, and, most likely, a different trajectory of development. Distinguishing among these possibilities and understanding the mechanisms underlying the effect of words on category learning is of critical importance for understanding cognitive development.

A. *Words are supervisory signals facilitating category learning*. One hypothesis is that words are invitations to form categories, that is, words function as top-down supervisory signals facilitating category learning. Evidence for this hypothesis comes from studies that use a variety of visual attention and object examination paradigms. Waxman and Markow's (1995) study was one of the first demonstrations of these effects. In this study, 9- to 20-month-olds were presented with a task that combined object examination and novelty preference. First participants were presented with four familiarization trials. On each familiarization trial they were given one object to play with. During familiarization, the category structure (i.e., *basic level* versus *superordinate*) was fully crossed with labeling condition (*noun* versus *no word*), thus resulting in four between-subjects conditions. In one condition all familiarization objects were drawn from a single basic-level category such as cars, whereas in the other condition all objects were drawn from a superordinate category that included cars and airplanes. In addition, in one condition, a label in the form of the count noun accompanied the familiarization objects (e.g., "Look, a car), whereas in the other condition no labels were introduced (e.g., "Look!"). Then participants were presented with a single test trial that included a new member of the familiarized category and a new member of a contrasting category (e.g., car versus airplane in the basic-level condition or truck versus lion in the superordinate condition). Results indicated that participants were above chance in all conditions, except for the superordinate category–no-word condition. These results led researchers to conclude that words facilitate infants' attention to superordinate categories.

However, these data are inconclusive for several reasons. First, given the age range of infants (i.e., 9 to 20 months), it is likely that some infants knew the categories whereas others were just learning them. In addition, the study seems to be underpowered, with only 32 infants participating in four conditions and each participant contributing only one test data point. In another study (Balaban & Waxman, 1997), 9-month-olds were familiarized with nine pictures depicting items from the same basic-level category (e.g., rabbits), with familiarization items accompanied by either nouns or nonlinguistic sounds (i.e., tones). At test participants were presented with two test trials, depicting a novel item from the studied basic-level category (e.g., a novel rabbit) and a member of another basic-level category drawn for the same superordinate category (e.g., a pig). Although the researchers found a difference between the word and the tone condition, the direction of the difference was quite ambiguous: Participants in the tone condition exhibited familiarity preference whereas participants in the word condition exhibited no preference. In addition, the absence of a silent baseline condition makes these findings even more difficult to interpret because it is impossible to tell which condition drives the putative effect. Is it the case that words differ from the baseline condition or is it the tones?

A later study by Fulkerson and Haaf (2003) addressed the preceding problem by including a silent baseline. In this study 9- and 15-month-olds were presented with an object examination task. In addition to age, two variables were manipulated: category structure (basic level versus superordinate level) and sound condition (silent, nonlinguistic sound, or word). Participants were presented with six familiarization trials (on each trial they examined a member of the studied category). Participants were then given two test trials, one depicting a member of the studied category and another depicting a member of a new category. Similar to the experiments described earlier, sounds were introduced only during familiarization, but not during testing. Results indicated that participants ably categorized at the basic level regardless of the sound condition (which contradicted the findings reviewed earlier). At the same time, for the global level, participants were more likely to exhibit novelty preference in the word condition. Note, however, that (a) conditions were never compared to each

other directly and (b) for each age group in the global condition, there were five *t*-tests, which represents a threat to statistical significance, had these test been corrected for multiple comparisons.

Finally, Waxman and Braun (2005) directly compared categorization between label and silent conditions in 12-month-olds. Infants were familiarized with four items from a superordinate category (e.g., four toy animals) with items either being labeled by nouns ("Look! It is a Keeto") or presented without labeling (e.g., "Look at this"). They were then presented with a single test pair consisting of a novel animal and a novel tool. Results indicated above-chance novelty preference in the noun condition, but not in the no-word condition. However, it was not reported whether the two conditions differed from each other, thus rendering the results inconclusive.

Although these effects of words on category learning in infancy appear tenuous, there are two other potential sources of evidence. One of these sources has to do with putatively different effects of nouns and adjectives on categorization. In one study (Booth & Waxman, 2009), 14-month-olds and 18-month-olds were familiarized with items of the same color that were drawn either from the same basic-level category (e.g., purple horses) or from the same superordinate category (e.g., purple animals). In one condition, members of a category were referred to by a count noun (e.g., this one is a blicket), and in the other condition they were referred to by an adjective (e.g., this one is blickish). At test participants were presented with a member of a familiar category (e.g., green horse) and a member of a novel category (e.g., purple chair). Item presentation at test was split into four time windows (i.e., 0–1 seconds, 1–2 seconds, 2–3 seconds, and 3–4 seconds). The analyses revealed greater novelty preference in the noun condition compared to the other two conditions, but only for the Time Window 3 (i.e., 2–3 seconds after the stimulus onset). Is Time Window 3 special or do the results stem from multiple comparisons? We cannot answer this question, but in a similar study conducted by the same researchers with a slightly different paradigm (Waxman & Booth, 2002), 14-month-olds exhibited equivalent novelty preference in the noun and in the adjective conditions. Therefore, evidence for different effects of nouns and adjectives on category learning in infancy is rather weak and inconclusive.

Another source of evidence pertains to effects of words on inductive inference (e.g., Graham & Kilbreath, 2007; Keates & Graham, 2008; Welder & Graham, 2001). In most of the studies researchers familiarized participants with an item having a hidden feature (e.g., producing rattling sound when squeezed). Following familiarization, participants were presented with either high-similarity or low-similarity test items. Of interest was participants' willingness to generalize target actions to novel items. Both at training and at testing, objects were accompanied (a) by count nouns in the referential frame (e.g., "This is a blick"), (b) by count nouns presented in isolation ("Blick"), (c) by adjectives in the referential frame ("This is blickish"), or (d) in silence. Results indicate first, that around 13 months of age labels facilitate inductive inference to low-similarity items and, second, that around 16 months of age, facilitative effects of words become specific such that count nouns are more likely to produce these effects than are other word forms. However, the source of these effects is unclear. In particular, given that labels were presented both at training and at test, it is possible that labels are just better memory cues for the target property than are other cues. To provide a stronger test of whether labels serve as category markers it would be better to present labels during familiarization but not at test, an approach that was attempted in the infant categorization studies by Waxman and colleagues reviewed earlier.

B. *Words start out as features but become supervisory signals in the course of development*. The second hypothesis is that words start out as perceptual features affecting processing of visual input but that the effects of words may change over the course of development.

Early in development words may hinder category learning by attenuating processing of visual input, whereas later in development words may contribute to category learning by increasing within-category featural overlap. Critically, in both cases words function as perceptual features. For example, Sloutsky and colleagues have presented evidence that novel labels and other sounds overshadow (i.e., attenuate) the processing of visual stimuli in young infants (Robinson & Sloutsky, 2004, 2007b, 2010; Sloutsky & Robinson, 2008). As a result, auditory stimuli (including novel words) interfere with category learning (Robinson & Sloutsky, 2007a; Sloutsky & Robinson, 2008).

The overshadowing hypothesis is based on a series of familiarization and habituation studies in which infants were familiarized with compound auditory-visual stimuli (e.g., pairing a picture of a cat with a word or with a non-linguistic sound) and were then exposed to a dishabituation stimulus that changed either the auditory or the visual component of the compound stimulus. At test, infants noticed the change in the auditory component but not the change in the visual component. Failure to dishabituate to

a change in the visual stimulus when it was accompanied by a sound (but not when it was presented in silence) suggested that the auditory stimulus interfered with processing of the visual information (i.e., overshadowed it) during familiarization. It should be noted that familiar auditory stimuli, such as well-known names, do not produce such dramatic overshadowing effects in infants. Furthermore, novel words interfere with visual processing at younger ages (i.e., 10 months of age and younger) but the effect is reduced in older infants (i.e., 16 months of age and older; Sloutsky & Robinson, 2008).

Because of the increased efficiency of cross-modal processing, overshadowing weakens in the course of development (Robinson & Sloutsky, 2004; Sloutsky & Napolitano, 2003). For older infants and young children, overshadowing has an impact on processing of infrequent features (e.g., individual idiosyncratic visual features of category members) and not of frequently recurring features (e.g., features shared by most category members). As a result, for these older participants, words may facilitate detection of what is common among category members, but they may undermine detection of individual features, thereby hindering the recognition of the distinction between familiar and new category members.

Although words may begin as features that affect the processing of visual input, they eventually may become supervisory signals. For example, Plunkett and colleagues (2008) presented experimental evidence suggesting that for preverbal infants, effects of words on category learning are not straightforward: Under some conditions, words may facilitate category learning, under other conditions they may hinder category learning, and yet under other conditions, they do not affect category learning at all. To better understand this pattern of findings, Plunkett and colleagues (Gliozzi et al., 2009) developed a computational model to simulate these patterns of infants' responses. The model handled visual and acoustic information in an identical fashion, with no direct connections between objects and labels. In other words, the learning process was unsupervised. The pattern of novelty preferences in the simulations mimicked closely the infants' preferences. This finding suggested that an unsupervised learning device, which performs statistical computations on compound visual and acoustic stimuli, offers a viable solution to the problem of how labels influence category formation in the infant experiments. Although Gliozzi et al. (2009) provide support for the idea that words start as features, other research suggests that words do not have to remain features. As children develop, they may learn that words have high predictive power in determining a category, and, as a result, words may become supervisory signals. While there is little disagreement among theorists that words eventually become invitations to form categories (cf. Casasola & Bhagwat, 2007; Lupyan, Rakison, & McClelland, 2007; Mayor & Plunkett, 2010; Sloutsky, 2010; Yamauchi & Markman, 1998), the precise developmental time course of this transformation remains unclear.

### Summary

In sum, infant category learning is the first critical step in conceptual development. Category learning emerges early in life and infants are proficient category learners. Although researchers generally agree that infants learn progressively more complex categories, many issues in the development of categorization remain a matter of debate. Among the most controversial issues are whether concepts emerge from perceptual categories learned by infants and the role of language in infant category learning.

Despite these controversies, most researchers agree that infants learn a variety of categories, some of which come to acquire conceptual significance for children and adults. Perhaps the most critical step in acquiring conceptual significance is lexicalization, or learning names for categories. These names eventually become part of category representation and knowledge hubs that help connect what is known about a given category. Words are also important for forming conceptual hierarchies, such as dog → mammal → animal → living things → objects. These conceptual hierarchies support propagation of knowledge though inductive, deductive, and transitive inference. For example, upon learning that all objects are made out of atoms, one may conclude (by deduction) that dogs are made out of atoms, too. Similarly, upon learning that dogs are mammals and mammals are animals, one may conclude (by transitive inference) that dogs are animals. And finally, upon learning that dogs have white blood cells, one may infer (by induction, and thus with only a degree of certainty) that mammals have white blood cells, too. It is not clear if these hierarchical relations can be expressed without language, at least without quantifiers such as *all*, *some*, and *some are not*, and we contend that language plays a critical role in conceptual development following infancy. The next section focuses on these issues.

## CONCEPTUAL DEVELOPMENT AFTER INFANCY

A great deal of conceptual development takes place in postinfancy years. Obviously, there are multiple candidate

sources of this development. Children continue acquiring language. They receive increasing input from multiple informal sources, including from parents and other family members, peers, and books and media, to name a few. Children continue expanding their knowledge base that provides a foundation for acquisition and organization of additional knowledge. Their processing capacity including working memory and selective attention also undergoes substantial development. And they receive systematic input from formal educational sources such as classroom materials and textbooks. It is likely that all these factors contribute to postinfancy conceptual development, albeit in different ways and to different degrees. In what follows, I consider the role of cognitive and linguistic factors in conceptual development, followed by a discussion of some of the specific achievements of semantic development, including the development and organization of semantic knowledge, the development of conceptual hierarchies, and the development of inductive inference.

## The Role of Cognitive and Linguistic Factors in Conceptual Development

One of the most striking changes in postinfancy development is a dramatic expansion of processing capacities coupled with dramatic growth of lexical and grammatical aspects of language. As was argued elsewhere (Sloutsky, 2010), these developments are likely to significantly affect conceptual development.

### *The Role of Cognitive Factors in Conceptual Development*

Young children experience dramatic changes in basic cognitive processes during the postinfancy years, including the development of long-term memory (Ghetti & Lee, 2010; Newcombe, Lloyd, & Ratliff, 2007), working memory and other aspects of executive function (Carlson, 2005; Cowan, 1997), and selective attention (Hanania & Smith, 2009; Plude et al., 1994). Given the role of selective attention and memory in adult category learning and categorization (Nosofsky, 1986, 1988), it is likely that these developments are important contributors to conceptual development.

Although there is little direct empirical evidence linking growth in basic cognitive processes to conceptual development (but see Halford, Andrews, & Jensen, 2002, for such possibility), there is indirect evidence. For example, Kloos and Sloutsky (2008) examined the ability to learn categories of different statistical structure across development, with some of the categories having multiple overlapping features (i.e., statistically dense categories) and others having few category-defining features (i.e., statistically sparse categories). Although the researchers did not find differences between 4- to 5-year-olds and adults in learning the former categories, they did find evidence of profound differences in learning the latter categories (see Figure 12.7). Given that learning of sparser categories puts demands on selective attention, these findings indirectly implicate selective attention in the development of categorization. Other researchers (e.g., Hammer, Diesendruck, Weinshall, & Hochstein, 2009) reported related findings using different categories and category structures.

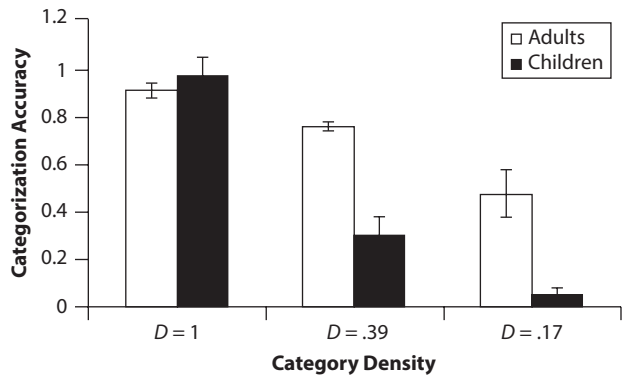


**Figure 12.7** Unsupervised category learning by density and age group after Kloos and Sloutsky (2008).

Another study indirectly implicating selective attention in the development of categorization (albeit with younger participants) was reported by Son, Smith, and Goldstone (2008). In this study toddlers learned shape-based categories in one of two conditions, either through perceptually impoverished examples that communicated primarily shape information or through perceptually rich, realistic items. Participants' category learning was then tested with either impoverished or rich stimuli. Results indicated that regardless of the testing stimuli, participants exhibited more robust learning when trained with impoverished stimuli. Given that perceptually rich stimuli carry much information that is not relevant for category learning, these stimuli are likely to put greater demands on selective attention than the impoverished stimuli, and young participants cannot meet these demands due to immaturity of selective attention.

### *The Role of Language in Conceptual Development*

Although there is little disagreement that language plays a critical role in conceptual development, what exactly this role is, how it changes in the course of development, and how it differs for different kinds of concepts is a matter of debate. In particular, sometimes words denote already existing perceptual categories that are likely to be acquired

in infancy (e.g., Dog, Ball, or Cup). Sometimes words are a starting point for forming nonperceptual categories (e.g., Love, Fairness, or Memory). And sometimes language interacts with other aspects of experience to help form important ontological distinctions that are necessary for the development of conceptual hierarchies.

*Learning words for already-known categories*. As discussed earlier, there are many situations in which categories have enough statistical structure to enable them to be learned perceptually. Typically these are statistically dense categories of objects, many of which are present in the environment surrounding the infant. In these situations, words are likely to follow category learning and thus are mapped onto these preexisting categories (Merriman, Schuster, & Hager, 1991; Mervis, 1987). What do words do if a child acquires a lexical entry for an already-known category (e.g., a word *dog* for a perceptual category Dog)? One possibility is that, at least initially, in these situations words function as features, thus simply contributing to the featural overlap among category members. Although I am not aware of any direct evidence supporting this contention, there is a growing body of indirect evidence.

First, there is evidence that shared labels contribute to similarity of the items (Sloutsky & Fisher, 2004a; Sloutsky & Lo, 1999; Sloutsky, Lo, & Fisher, 2001). In a number of studies, 4- to 5-year-olds were presented with a target and two test items and asked which of the test items looked more like the target. In one condition, there were no labels, whereas in another condition, labels were introduced, such that one test item shared the label with the target (e.g., both were called "a dax") and another had a different label. The results indicated that items that shared the label were perceived as looking more similar than the same items introduced without labels. There is also evidence (Sloutsky & Fisher, 2012) indicating that young children were more likely to infer that two items have similar properties when the items were accompanied by phonologically similar labels than when the items were accompanied by different labels. These effects should not have been observed if young children construed linguistic labels as symbols rather than as a feature of items.

Second, Deng and Sloutsky (2012) provided evidence that salient visual features have greater effects on category learning than do words. These researchers adopted a paradigm introduced by Yamauchi and Markman (1998, 2000) to distinguish between whether labels function as features or category markers.

The paradigm is based on the following idea. Imagine two categories, A (labeled "A") and B (labeled "B"), each having five binary dimensions (e.g., Size: large versus small, Color: black versus white, etc.). Because the dimensions are binary, one value on each dimension can be denoted by 0 and another by 1 (e.g., white = 0, black = 1). Further, imagine the prototype of Category A has the value of 1 for all dimensions (i.e., "A," 1, 1, 1, 1, 1), whereas the prototype of Category B has the value of 0 for all dimensions (i.e., "B," 0, 0, 0, 0, 0).

Items derived from these prototypes can be used in two interrelated generalization tasks—classification and projective induction. The goal of classification is to infer category membership (and hence the label) on the basis of presented features. For example, participants are first presented with all the values for an item, such that all the values except one come from Category A. Participants are then asked to predict the label (e.g., ?, 0, 1, 1, 1, 1). In contrast, the goal of induction is to infer a feature on the basis of category label and other presented features. For example, participants are given an Item A with features 1, ?, 1, 0, 1 and are asked to predict the value of the missing feature.

A critical manipulation that could illuminate the role of labels is the "low-match" condition. For low-match induction, participants were presented with an Item A as ?, 0, 1, 0, 0 (thus more similar to the prototype of Category B) and asked to infer the missing feature. For low-match classification, participants were presented with an Item ?, 1, 0, 1, 0, 0 (which again was more similar to the prototype of Category B) and asked to infer the missing category label.

In both cases, items are more similar to Prototype B and, if labels are category markers, participants should be more likely to infer the missing feature as belonging to A (i.e., the induction task) than to infer label "A" (i.e., the classification task). In contrast, if the label is just another feature, then a different pattern should emerge: Relative performance on classification and induction tasks should depend on attentional weights of labels compared to those of other features. Specifically, if there are features with a higher attentional weight than the label, then a classification task (when a highly salient feature could be used to predict the label) should yield more A responses than an induction task (when the label is used to predict the highly salient feature). Deng and Sloutsky (2012) found that when all features were of comparable salience, 4- to 5-year-olds (in contrast to adults) tended to rely on the overall similarity rather than on category label. Furthermore, when the label was pitted against a highly salient visual feature (i.e., pattern of motion), 4- to 5-year-olds relied on the single most salient feature.

*Learning words for yet unknown categories*. Even if words are features early in development, they do not have to remain features throughout development. First, there is evidence from the earlier studies indicating that adults are more likely to treat words as symbols rather than as features. In addition, many concepts are learned in the order opposite to the one described earlier. That is, in contrast to the order of acquisition described earlier (i.e., from prelinguistic categories to words), many concepts start with words. For example, around 4 years of age a child may know words such as *love*, *number*, or *history* (MRC Psycholinguistics database, http://websites.psychology.uwa.edu.au/school/MRCDatabase/uwa_mrc.htm), but it is quite unlikely that the child knows all these underlying concepts. Although I am unaware of any research examining this issue, it is hard to see how words can be features in these situations. It is more likely that in these circumstances words denote a category that is yet to be acquired.

## INTERACTION BETWEEN LANGUAGE AND OTHER ASPECTS OF THE EXPERIENCE

There is evidence that as early as 24 months children exhibit an understanding of broad ontological distinctions, such as the distinction between objects and substances (e.g., Soja, 1992; Soja, Carey, & Spelke, 1991). How do children develop such understanding? Some have suggested that language (in the form of count/mass noun syntax) is instrumental in the acquisition of the ontological categories of object and substance (Quine, 1960), whereas others have proposed that these broad ontological distinctions precede language and are thus independent of it (Soja, 1992; Soja et al., 1991). In contrast to these single-cause accounts, L. B. Smith and colleagues (e.g., Samuelson & Smith, 1999) proposed that perceptual cues (e.g., solidity) and linguistic cues (e.g., mass versus count noun syntax) jointly contribute to the acquisition of broad ontological distinctions. To test these ideas they asked two interrelated questions. First, they asked whether solidity is correlated with syntax: Are solid things more likely to me labeled with count nouns and are substances more likely to be labeled by mass nouns? They also asked whether solidity is correlated with category organization: Are solid things more likely to be organized by shape, and are nonsolid things more likely to be organized by material? To answer these questions, they selected a corpus of 312 nouns taken from the toddler form of the MacArthur Communicative Development Inventory (Fenson et al., 1994). They then asked adult participants to describe the solidity versus nonsolidity of items named by each noun, and to describe the similarities in shape, material, and color of the instances named by each noun. Their findings are graphically presented in Figure 12.8. These results indicate that although syntax, solidity, and category structure do not overlap completely, there is a high level of correspondence among the three: Solids, unlike nonsolids, are more likely to be referred to by count nouns and to be organized by shape.

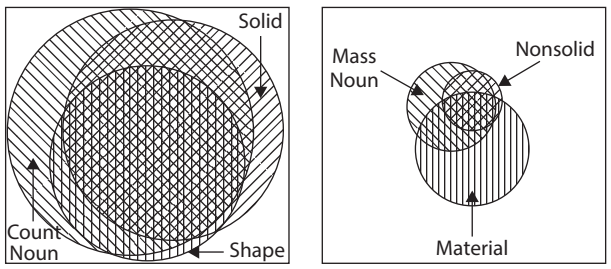


**Figure 12.8** Codependency of solidity, shape, and syntax in early vocabulary after Samuelson and Smith (1999).

### The Development of Semantic Knowledge and Its Role in Conceptual Development

As discussed previously, language is not a necessary aspect of category learning: Nonlinguistic animals and prelinguistic infants can learn categories. However, lexicalization of categories (i.e., learning words for these categories) is a critical step in acquiring and integrating knowledge about the world. First, language allows one to efficiently encode, store, and retrieve information about the category. Second, language allows one to acquire information that goes beyond one's own experience (e.g., owls are awake at night) or not observable directly (e.g., vegetables have vitamins). And third, language allows the establishment and communication of nontrivial commonalities (e.g., plants and animals are alike in that they need water to survive). And finally, language allows the development of a conceptual network (also referred to as sematic knowledge) that represents one's knowledge about the world (see Landauer & Dumais, 1997 for computational evidence).

Semantic memory is the system that stores semantic knowledge—information about concepts, facts related to these concepts, and words denoting them (see Tulving, 1972). Various tasks can be used to examine semantic memory, including picture naming, word-to-picture matching, sorting, category verification (e.g., is cat an animal?), and property verification (e.g., do cats have wings?).

The idea of semantic memory raises questions such as, How is knowledge represented in semantic memory? And how do these representations change in the course of development? Several proposals have been advanced to answer these questions.

### *The Hierarchical Propositional Approach*

The hierarchical propositional approach stems from the work of Quillian (1967) and Collins and Quillian (1969). They were concerned with the modeling of the human conceptual system, their modeling being guided by the overall idea that concepts are organized hierarchically and stored as nodes in a network. Each node is linked to facts (or propositions) that are true of all (and only of) members of a given category and its constituent subcategories. Therefore, for example, facts stored about "canary" should be specific to canaries (but not necessarily to all birds), such as "is yellow" and "can sing," while facts stored about the bird should be specific to all birds, such as "has wings," "has feathers," and "lays eggs" (see Figure 12.9).

The advantage of this system of organization of knowledge is that, given that propositions are true of all members of a superordinate category, these propositions need be stored only once, at the level of the superordinate category (see T. T. Rogers & McClelland, 2004, for a discussion). If a fact, such as "lays eggs," is linked to birds, there is no need to link it to canaries as well. Another advantage of this system of storage is that it supports reasoning: Knowledge can be propagated downward by deduction (All birds have wings. X is a bird. Therefore X has wings). However, because only specific information is stored about lower-level categories (i.e., information that distinguishes these from higher-level ones), the ability of this system to support inductive inference is less clear.

To test the system, Collins and Quillian (1969) presented adult participants with property verification sentences (e.g., "Robins can fly") and category verification sentences (e.g., "A robin is a bird"). The authors predicted that people have faster access to information stored in a given node than to information stored in a superordinate node. As a result, participants should respond faster to category verification questions such as "Is a canary a bird?" than to "Is a canary an animal?" They should also respond faster to property verification questions related to a particular level (e.g., "Can a canary sing?") than to those related to a superordinate level (e.g., "Does a canary have skin?"). All these predictions were confirmed empirically, thus suggesting that this model captures important properties of the human conceptual system.

Despite the early success of the model, subsequent researchers presented evidence that was difficult to reconcile with the model's predictions (see T. T. Rogers & McClelland, 2004, for an extensive review). First, contrary to the model predictions, reaction times in property-verification tasks were influenced by factors that had little to do with the position of the property in the taxonomic hierarchy (e.g., feature typicality and frequency). In addition, for many categories, the time it took to verify category membership differed from the model's predictions. Although closer higher-level categories should be identified faster than remote ones (e.g., the judgment that "X is a bird" should be faster than "X is an animal"), people are in fact faster to judge that a chicken is an animal than that it is a bird (Rips, Shoben, & E.

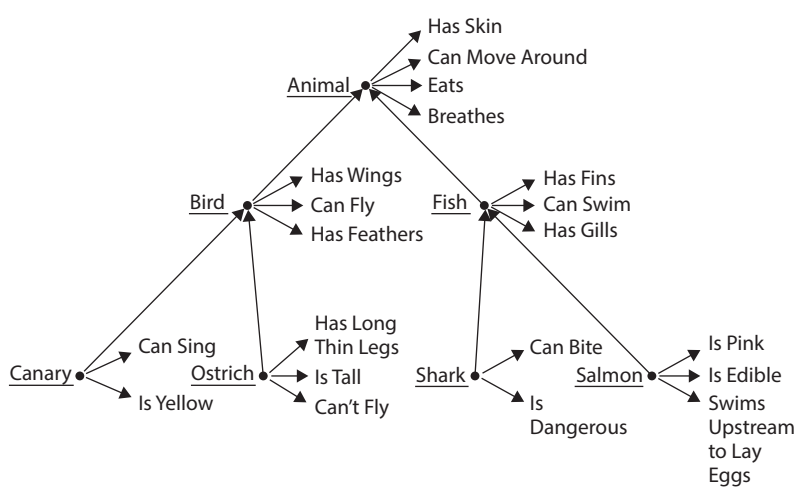


**Figure 12.9** An example of three-level hierarchy from Collins and Quillian (1969).

E. Smith, 1973). And finally, some researchers argued that "there is something paradoxical about the model; the essential message from development and disintegration is that the general properties of concepts are more strongly bound to an object than its more specific properties, but in Quillian's model the specific properties are stored closest and are therefore most strongly associated with a concept" (McClelland & T. T. Rogers, 2003, p. 311). In particular, evidence from neuropsychological studies (e.g., Warrington, 1975) demonstrated that in the case of a neurodegenerative disease, such as semantic dementia, patients do not lose information about all concepts at once: More specific information is lost earlier than more general information (see also T. T. Rogers et al., 2004; T. T. Rogers & McClelland, 2004). For example, patients tended to name objects at the superordinate rather than a more specific level (e.g., "tool" instead of "hammer"). These patients were more likely to lose more specific information (e.g., the size of a particular animal), while retaining more general information (e.g., that it is an animal). On the basis of these data, Warrington (1975) suggested that specific information is not only the first to be lost, but is also the last to be acquired in the course of development: "blunt broad concepts gradually [become] differentiated" (p. 655).

### *The Connectionist (PDP) Approach*

The fundamental assumption of the connectionist approach is that abstract semantic representations emerge as a product of domain-general statistical learning: Modality-specific perceptual representations provide the input to semantics, and modality-specific response systems permit the expression of semantic knowledge. Because the semantic system receives input from multiple modalities as well as linguistic input, representations formed as a result of learning are not tied to any particular modality, but rather capture the deep structure across modalities (T. T. Rogers et al., 2004). Two specific models are worth considering: one that accounts for the deterioration of semantic memory in the course of semantic dementia (T. T. Rogers et al., 2004) and another that addresses issues of conceptual development (T. T. Rogers & McClelland, 2004).

The model developed by T. T. Rogers et al. (2004) is presented in Figure 12.10. Critical components of this model are that (a) the input layer receives perceptual input from vision (and perhaps from other modalities) as well as from different kinds of verbal input and (b) similar information could be received through different inputs (e.g., the fact that a bird moves might be observed directly or through verbal communication). All these input units are bidirectionally connected with the set of units in the hidden (semantic) layer. In neural networks, the hidden layer is not directly connected to the world, and it mediates the signal from the input layer to the output layer. Therefore, the semantic units in the hidden layer do not receive direct, external inputs from the environment, and semantic knowledge emerges as a distributed pattern of activity over visual and verbal input. T. T. Rogers et al. used information from a variety of tasks (e.g., attribute listing and drawing) to estimate the structure of the input. Results indicated that the model accurately captured the similarity structure emerging from these tasks in healthy adults and in patients with semantic dementia. According to this model, semantic dementia is a result of deterioration of the semantic layer that roughly corresponds to the anterior and inferolateral

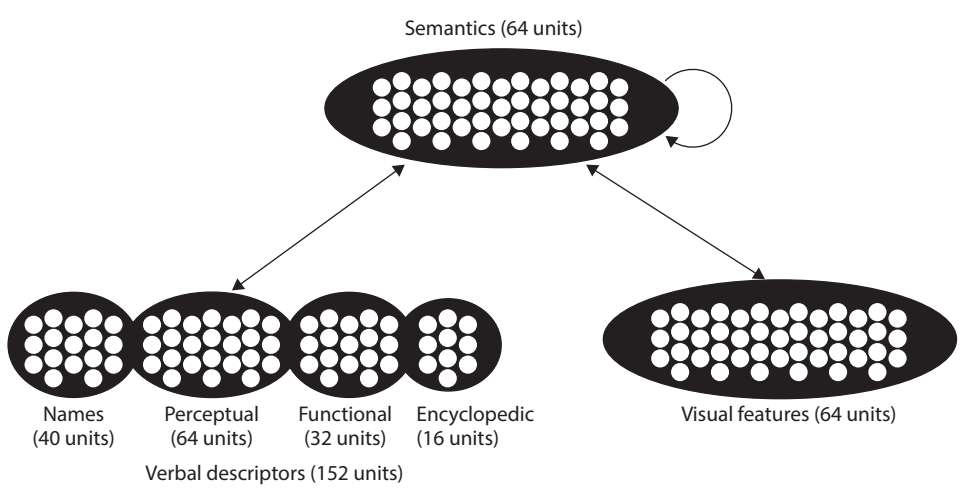


**Figure 12.10** Architecture of T. T. Rogers and colleagues' (2004) model.

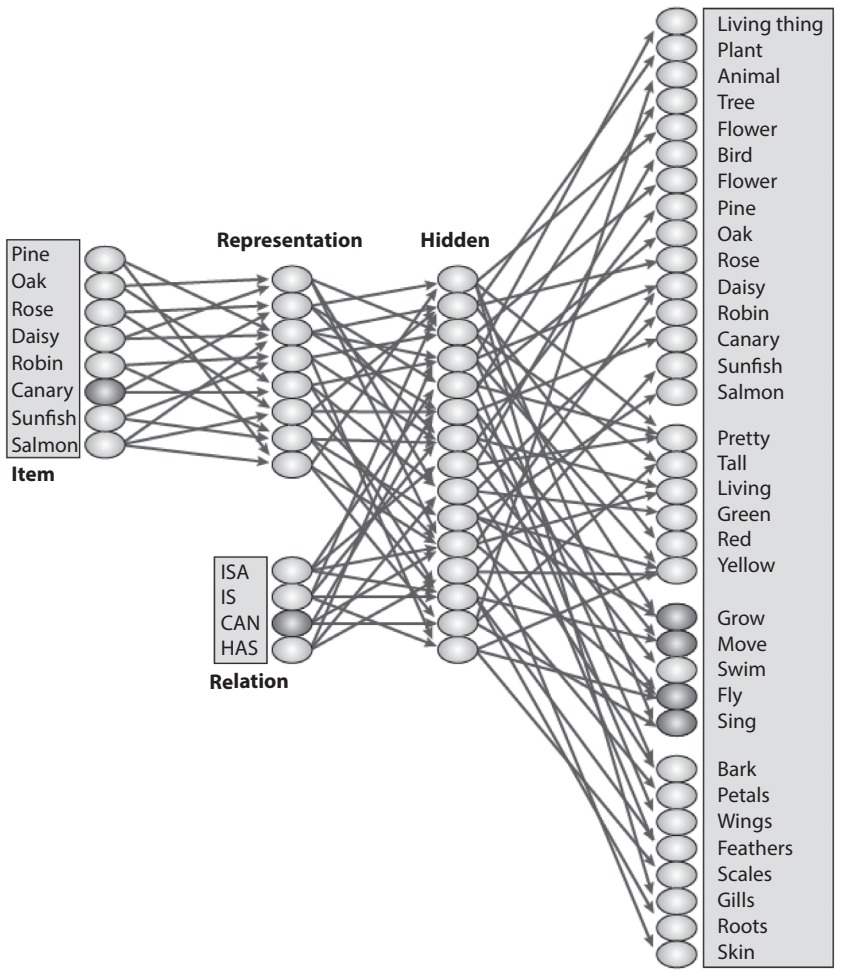


**Figure 12.11** Network architecture developed by Rumelhart and Todd (1993) and used by T. T. Rogers and McClelland (2004).

regions of the temporal cortex, both of which exhibit signs of progressive atrophy in the course of semantic dementia.

The second model (T. T. Rogers & McClelland, 2004) is a variant of a connectionist network developed by Rumelhart and Todd (1993) and uses a slightly different architecture (see Figure 12.11). The network learns propositions about the concepts and activation is propagated from left to right. Input consists of a concept–relation pair (e.g., the input "Rose HAS"), and the network is trained to turn on all those output units that represent correct completions of the input pattern. Similar to the model discussed earlier, semantic representations that cohere in the "Representation" and "Hidden" layers are distributed patterns of activation that emerge as a result of learning. T. T. Rogers and McClelland (2004) developed two variants of the model, one in which item information was represented in a local manner as a separate node and another variant in which item information was represented in a distributed manner, that is, as pattern of activation over attributes. Although the details of learning in the model are outside of the scope of this review, it is important to note that the network itself is feed-forward in that activation propagates forward, but the error propagates backward using a variant of supervised learning known as the back propagation algorithm (Rumelhart, Hinton, & Williams, 1986). In many variants of supervised learning, the system responds to a query and then receives feedback as to whether the response is correct or not. Learning is construed as the process of error reduction, and back propagation is a formal way of reducing the error.

A critical component of the model is the idea of coherent covariation, that is, co-occurrence of a set of properties across different category members. Coherent covariation is distinct from simple correlation in that it generally refers to the cooccurrence of multiple rather than just two properties. For example, having wings, having feathers, having beaks, living in nests, having hollow bones, and

being able to fly all consistently co-occur in birds. The model accounts for a variety of developmental data, most importantly, for progressive differentiation of concepts in the course of development. Progressive differentiation is the idea that broader categorical distinctions (e.g., the distinction between animates and artifacts) is acquired prior to more specific categorical distinctions (e.g., the distinction between cats and dogs).

The T. T. Rogers and McClelland model offers a mechanistic account of semantic development, it makes clear theoretical predictions, and it explains some of the best-known developmental findings. However, many theoretical ideas advanced by T. T. Rogers and McClelland are yet to be tested in empirical studies. In particular, it will be important to systematically measure developmental changes in the structure of semantic memory and to examine whether the model captures these changes. It is also worth mentioning that progressive differentiation is the only process of semantic development captured by the model. It is not clear whether this process is capable of learning abstract concepts (e.g., legal, scientific, or mathematical) that combine items that have few commonalities (and thus require the learner to ignore differences between instances of a concept).

### *Graph-Theoretical Approach to Semantic Development*

Another way of examining the semantic structure is a graph-theoretical approach (e.g., Hills, Maouene, Maouene, Sheya, & L. B. Smith, 2009; Steyvers & Tenenbaum, 2005) that captures the ways in which concepts are related within a conceptual network. An extensive treatment of the graph-theoretical approach is presented elsewhere (Steyvers & Tenenbaum, 2005), and I consider here only the basic concepts of the approach and the ways it captures development.

According to this approach, any semantic network can be described as a graph that consists of a set of nodes and a set of edges that connect individual nodes. Two connected nodes are considered to be neighbors, and a node and all its neighbors are considered a neighborhood. The approach allows for a number of quantitative measures, including the size of the network (i.e., the number of nodes) and the clustering coefficient. The latter is determined by calculating the number of connections between the nearest neighbors of a given node and the total number of possible connections. Hills et al. (2009) used this approach to examine the network of nouns that were learned early by 2.5-year-olds. The nouns were selected from the toddler version of the MacArthur-Bates Communicative Developmental Inventory (MCDI; Fenson et al., 1994). Feature norms for these nouns were derived from McRae, Cree, Seidenberg, and Mcnorgan (2005), who presented 725 participants with 541 nouns denoting living and nonliving things and asked the participants to list features of items denoted by these nouns. Hills et al. (2009) selected a list of 130 nouns from the 312 nouns on the MCDI. In the network, nodes represented nouns and edges represented features shared between noun pairs. Of course, each noun pair may share many features or only a few, and therefore the resulting network depends on the connectedness threshold or $w$, the minimal number of shared features that is interpreted as an edge.

The goal of the network analysis was to answer two questions: how well toddlers' basic-level concepts are organized into superordinate categories and how perceptual and conceptual features contribute to that organization. To answer the first question the resulting networks were analyzed by calculating the clustering coefficient, which was then compared to a control random network with an equivalent number of nodes. When a network has a high average clustering coefficient relative to the appropriate random control network, it indicates the existence of subnetworks or higher order, superordinate categories. It was found that when $w = 1$, there was only one densely connected network: When nouns share very few features, everything is connected to everything else and no structure emerges. However, when $w$ was set to 2, 3, or 4, structure was more apparent. When clusters of nouns shared multiple overlapping features (the $w = 4$ network), the resulting network has clusters of nouns representing animals, vehicles, foods, clothes, and household objects. Therefore, structure may emerge in the course of development as children learn multiple properties shared by related nouns. This approach also offers an interesting possibility for studying the development of knowledge domains. As conceptual neighborhoods become increasingly more coherent and increasingly distinct from other neighborhoods, they may evolve into what is known as knowledge domains.

To answer the second question concerning the role of perceptual and conceptual features in the development of structure, McRae et al. (2005) divided the features into *perceptual* and *conceptual* ones. Stable perceptual properties of a thing (e.g., "has a tail") were identified as *perceptual features* and functional features (e.g., "used for transportation") were defined as *conceptual*. Network analyses indicated that perceptual features are more redundant and provide robust information about category inclusion, whereas conceptual features are rarer and provide a better

discrimination between categories. "A single conceptual relation is sufficient to define all category members that are, for example, *used for transportation*. No single perceptual feature contains that information" (Hills et al., 2009, p. 389). Therefore, both perceptual and conceptual features play important and perhaps complementary roles in early conceptual organization. Of course, this study is only the first step in understanding the early semantics and a number of important questions remain unanswered. First, the features for each of the toddlers' concepts (denoted by nouns) were taken from adult analyses (McRae et al., 2005), and adult features do not necessarily reflect those of toddlers. Second, both nouns and features reflected group rather than individual data and thus captured "a group toddler" rather than describing any individual child. Addressing these issues requires additional research.

### *The Origins of Semantic Knowledge*

The accounts previously reviewed suggest that semantic knowledge emerges from the learner's interactions with the world. However, no comprehensive account has yet been offered about how the abstract predicates (e.g., "ISA," which reflects a relation of class inclusion in T. T. Rogers & McClelland, 2004, or functional features, such as "used for transportation" in Hills et al., 2009) emerge from nonconceptual primitives.

In the absence of a complete account, there are a number of partial accounts. As discussed in the following, some have argued that semantic knowledge emerges from experience, whereas others have argued that components of semantic knowledge exhibit early onset and are unlikely to stem from individual experiences. One attempt to explain the development of semantic relatedness by linking it to experience was offered by Fisher and colleagues (Fisher, 2010; Fisher, Matlen, & Godwin, 2011). These researchers examined the development of semantic relatedness by presenting participants with verbal inductive arguments. For example, upon being told that dogs have property X, will participants generalize this property to semantically related items, such as puppies? The investigators selected semantically related (SR) items that were highly familiar to even the youngest participants (verifying this familiarity in a separate experiment). In addition, they also established through the analysis of Child Language Data Exchange System (CHILDES) corpus that some of the SR items tended to co-occur in the same sentence (e.g., bunny-rabbit), whereas others were unlikely to co-occur (e.g., crocodile-alligator). The results indicated that 4-year-olds generalized properties only when the SR items were co-occurring (e.g., from bunny to rabbit, but not from crocodile to alligator). In contrast, 6-year-olds (and some 5-year-olds) generalized even when SR items were not co-occurring. Therefore, between 4 and 6 years of age, children undergo semantic development and this development affects their pattern of inductive inference. So, what develops between 4 and 6 years of age? Perhaps children develop a more coherent taxonomy of their concepts and a better mapping of words on this taxonomy (cf. K. Nelson, 1974, for related arguments). Or perhaps some other changes are at the heart of semantic development. A detailed developmental account of these findings is yet to be provided.

There is also an argument that some components of semantic knowledge are unlikely to stem from individual experience. For example, some researchers argue that even young children attach special significance to information presented in the "generic" format (Cimpian & Erickson, 2012; Cimpian & Park, 2013). The generic format (e.g., *Dogs bark*) involves a statement that has an omitted existential quantifier "some" and thus should be equivalent to the statement *Some dogs bark*. However, research indicates that this format may be doing something different than existential quantification. In particular, it has been argued that even young children place special value on generic information, often inferring that it provides important insights about the world. For example, Cimpian and Scott (2012) presented 4- to 7-year-olds novel facts that were in either generic format (e.g., *Hedgehogs eat hexapods*) or nongeneric format (e.g., *This hedgehog eats hexapods*). Children were then asked whether other people (e.g., their parents or grown-ups in general) knew these facts. It was found that children were more likely to expect adults to know facts that had been presented in the generic format. Cimpian and Markman (2009) also reported that features presented in the generic format were more likely to be construed as causal. Although the mechanisms of the effect of generic format is not known, it is possible that people (including young children) interpret it as a universally quantified statement (e.g., *All X are Y*), suggesting that the statement describes the entire class (see Cimpian & Erikson, 2012). However, the effect is so far construed as reflecting a generic bias, which appears to be closer to describing rather than explaining the effect.

## The Development of Conceptual Hierarchies

One hallmark of conceptual organization is that it has a structure, and taxonomic organization of categories is an

example of such structure. Although taxonomies are not the only possible structure (see Kemp, Shafto, & Tenenbaum, 2012 for discussion of other possibilities), it is perhaps the most general and well-studied one. An example of such taxonomic hierarchy is Fido → dog → mammal → animal → living thing → bounded thing → thing. It is clear that such hierarchies are based on class-inclusion relations—they require including a set of mutually exclusive lower-level categories $A_i$ into a higher-level category B. For a system to be a hierarchy it has to satisfy two important constraints. First, lower-level categories should be exhaustive with respect to a higher-level category, such that $A_1 + A_2 + \ldots + A_i = B$. In practice, if not all subcategories are known, the exhaustiveness can be achieved by dividing B into A and its complement A', such that A + A' = B (e.g., animals consist of cats and noncat animals). The second constraint is that subclasses of B should be mutually exclusive, that is they should have no common members (i.e., the intersection of the two sets should be equal to 0: A ^ A' = Ø). It seems that a number of abilities should be in place in order for a taxonomic organization of concepts to be possible. First, there should be an appreciation of the logical constraints (e.g., understanding of the fact that the subclasses have to be mutually exclusive and that they are properly included in a larger class). Understanding of class inclusion relations manifests itself in understanding of quantifiers, such as *all*, *some*, *some are not*, and *none*. Second, there should be knowledge of words denoting higher classes: While a lower-level class can be derived from a higher-level class by using an adjective (*dog* + *adj* (small) = *small dog*), a higher order class for a dog cannot be derived and requires knowledge. And third (somewhat related to the second), there should be knowledge of a domain in which a taxonomy is to be built. In the absence of such knowledge it may not be clear which entities form categories and which categories are bound with class-inclusion relations and which are not. Of course, these abilities do not have to emerge all at the same time. Therefore, each of these abilities may represent a starting point for the development of conceptual hierarchies. Historically, a variety of candidate starting points have been considered. Some have argued that the development of conceptual hierarchies starts with logic, some have argued that it starts with language, and some have argued that it starts with domain knowledge.

### *Logic of Classes as a Starting Point*

In their classical book on the development of classification, Inhelder and Piaget (1964) considered the development of conceptual hierarchies as a function of the development of the logic of classes. The idea of the logic of classes is that multidimensional sets of stimuli can be divided into proper subsets by focusing on one dimension at a time, especially when dimensions are fully crossed. Therefore, as shown in Figure 12.12, Set S can be divided according to Dimension 1 into two mutually exclusive classes (e.g., Red objects A and Non-red objects A'). Group A can further divided into subsets B (e.g., angular objects) and B' (nonangular objects), whereas Group B in turn can be further divided into C (squares) and C' (nonsquared angular objects). Fundamental changes occur with respect to understanding of class inclusion relations and once these are mastered, a classification scheme based on these relations can be applied to any domain of knowledge. However, it easy to notice that logic alone may not be sufficient for building such hierarchies. In addition to logic, one needs to know dimensions that distinguish subcategories, which may be a nontrivial task. For example, whereas a division of objects into black and white ones is trivial, a division of animals into feline and canine animals may be not as trivial. Therefore, most contemporary theories consider domain knowledge as a necessary component of the development of conceptual hierarchies.

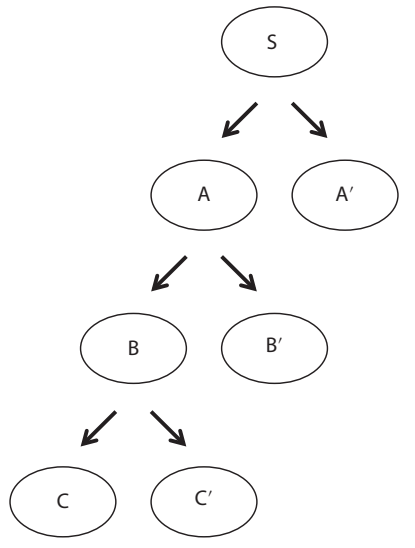


**Figure 12.12** Simple hierarchy based class-inclusion relations.

### *Domain Knowledge Approach*

As noted by Chi, Hutchinson, and Robin (1989), "in many instances, having knowledge in a specific domain can overcome any limitations that could have been imposed by the lack of global operators. Yet lacking knowledge in

a specific domain also can prevent adults from reasoning logically, even though they are presumed to have the logical operators" (p. 28)." Obviously, the same logical structure (i.e., class inclusion) may be based on different properties, and these properties may differ in their support of category coherence and inductive inference. For example, the property "has small parts" provides much weaker support for inductive inference than the property "has gills." In addition, lower level categories may share few attributes with higher-level categories or they may share many attributes (the same is true for individuals with respect to categories). The latter structure will result in greater coherence than will the former. A number of researchers (Carey, 1985; Chi et al., 1989; Inagaki & Hatano, 2002; Keil, 1981) subscribe to the view that a hierarchical organization of concepts may result from knowledge of a domain. In this case, class inclusion relations simply follow from a structural representation of a domain, without necessarily reflecting a more general ability to honor class inclusion. For example, mere knowledge of dinosaurs may help the child understand that all Brontosauri are dinosaurs, but not all dinosaurs are Brontosauri, without necessarily enabling the child to apply class-inclusion relations to unknown domains.

More recently, the assumption of hierarchical knowledge preceding the development of logic was used in a model of word learning proposed by Xu and Tenenbaum (2007). The model construes word learning as a variant of Bayesian inference and attempts to explain how young word learners select a referent for a newly learned word. For example, if a child is shown a terrier and it is called a *dax*, the child, according to Xu and Tennenbaum, needs to decide whether the word refers to terriers, dogs, or all animals. However, in contrast to other domain knowledge approaches, this model presumes a very early emergence of a conceptual hierarchy, which raises the question of where this hierarchy itself came from.

### *The Role of Language and Parental Input in the Development of Taxonomic Hierarchies*

Is it possible that language cues help children form hierarchies? There are a number of studies addressing this issue that have provided limited support for this idea. For example, Callanan (1985, 1989) examined whether the ways categories are labeled may affect children's interpretation of the referent class. It turned out that, when introducing new words referring to the superordinate level, parents are likely to anchor these at the basic level. In particular, when introducing the word *animal* (i.e., a superordinate category), a parent may point to a dog (i.e., a basic-level category) and say, "Here is a dog; it is a kind of animal." However, despite these strategies, 3- to 4-year-old children are highly unlikely to interpret new words as referring to superordinate categories (Callanan, 1989). Overall, evidence suggests that, at least for preschoolers, (a) spontaneous categorization at the superordinate level is rather rare and (b) parents rarely name items at the superordinate level.

### *Unresolved Issues*

Although it is likely that people eventually form conceptual hierarchies, the process of development is not well understood. Some (e.g., Piaget) argued for protracted (yet spontaneous) development, which is not fully completed until the stage of concrete operations, or perhaps, even later. Others argued that this ability transpires significantly earlier, with many preschoolers exhibiting evidence of conceptual hierarchies. However, evidence for the early onset of conceptual hierarchies is limited. Most importantly, even if a child exhibits the ability to classify items at a superordinate level or draws inductive inferences on the basis of a superordinate class, this ability does not necessarily indicate the presence of a conceptual hierarchy (see Halford et al., 2002). This is because these classifications or inferences may be driven by similarity (i.e., members of the same superordinate category are more similar to each other than to nonmember) rather than by their place in a conceptual hierarchy. It seems that a critical prerequisite of a conceptual hierarchy is the understanding of class inclusion, and this understanding may be missing early in development (e.g., Greene, 1994; Siegler & Svetina, 2006; Winer, 1980).

The second issue concerns factors affecting the development of conceptual hierarchies. Although there is a widely shared expectation that the development of conceptual hierarchies is spontaneous, there is little evidence that (at least early in development) parents label items at the superordinate level or attract children's attention to superordinate classes (Blewitt, 1983; Callanan, 1985, 1989). Therefore, it is possible that conceptual hierarchies are a consequence of formal education (Scribner & Cole, 1973). Although both issues remain unresolved, it seems fairly clear that the development of conceptual hierarchies in a given domain is based on at least two prerequisites: (1) understanding of class-inclusion relations and the logic of quantification and (2) knowledge of how these relations can be applied in a particular domain.

## The Role of Categories in Inductive Inference

There is general agreement that one of the central functions of categories is to subserve prediction (e.g., Anderson, 1991). Therefore, it is hardly surprising that the ability to draw inductive inferences has been used to probe conceptual development. Although several researchers have presented evidence for the ability of infants to perform induction, the majority of research on inductive inference focuses on verbal children. Several questions appear to be critical. What is the process of early induction and how does it change in the course of development? To what extent does prior knowledge constrain inference? How flexible is the inference? And what is the role of words in inductive inference?

### *Process of Early Induction*

Although it is well established that induction appears early in development (Gelman & Markman, 1986; Mandler & McDonough, 1996; Sloutsky & Fisher, 2004a; Welder & Graham, 2001), the process of early induction remains unclear. In an attempt to understand early induction, two theoretical proposals have been formulated—the knowledge-based approach and the similarity-based approach.

Mechanism

According to the first approach, early induction is a two-step process: First, people (including young children) identify the category of an entity and then generalize properties of the entity to other members of the category. Therefore, if told that a dog has a certain biological property (e.g., a particular type of heart) and then asked to generalize this property (e.g., "Who is more likely to have the same heart, another dog or a cat?"), people generalize the property to another dog because the two dogs belong to the same category. Therefore, even early in development induction is said to be *category based*. The ability to perform category-based induction hinges on a number of assumptions attributed to young children. Most importantly, young children are expected to hold the *category assumption*—a belief that individuals belong to general categories, with members of the same natural kind category sharing many important properties. In addition, young children are expected to hold the *linguistic* assumption—a belief that count nouns denote categories. Although it is not claimed that these assumptions are part of children's explicit knowledge, it is generally argued that early induction is based on them.

Support for the idea that early induction is category based comes from several sources. First, in a series of experiments, Gelman and Markman (1986) presented young children with a triad task, in which stimuli consisted of one target and two test items. The triad task was designed to pit appearance similarity against category membership: One test item belonged to the same category as the target but looked dissimilar from the target, whereas the other test item looked similar to the target, while belonging to a different category. Participants were presented with a triad and were informed that one test item had a particular hidden property (e.g., "hollow bones"), while the other test item had a different hidden property (e.g., "solid bones"). The task was to generalize a hidden property to the target. Category membership was communicated by using the same label for the target and the dissimilar test item. In general, children were more likely to generalize the property of the test item that shared the target's label than the property of the test item that shared the target's appearance (but see Sloutsky & Fisher, 2004a, Experiment 4, for diverging evidence and counterarguments). This finding was interpreted as evidence that children's induction is based on common category information.

According to the *similarity-based* approach, induction starts out as similarity based and becomes category based as a result of development. Although it is not known precisely when induction becomes category based, proponents of this approach argue that early induction is the same process as early categorization, with both being based on computing similarity between a presented item (or an item stored in memory) and a to-be-judged item.

Although proponents of both positions expect linguistic labels to affect induction, the processes assumed to drive these effects differ radically between these positions. According to the knowledge-based approach, labels affect induction because they denote category membership, with category information driving induction. According to the similarity-based approach, labels affect induction because they contribute to the perceived similarity of items, with similarity driving induction. Therefore, evidence that children rely on a category label in a triad induction task is not sufficient for distinguishing between the two positions.

One way of deciding whether induction is category based or similarity based is to examine memory traces formed during an induction task (Sloutsky & Fisher, 2004a; Sloutsky & Fisher, 2004b; see also Hayes & Heit, 2004, for a review). The idea is based on the following reasoning. There is a well-known "level-of-processing effect" in which deeper semantic processing facilitates memory so that there is better recognition of presented items (i.e., a

higher proportion of "hits"; see Craik & Lockhart, 1972; Craik & Tulving, 1975). There are, however, several studies indicating that deeper processing results not only in higher hit rates but also in more memory intrusions, that is, false recognitions of nonpresented items that are "critical lures," or items that are semantically associated to the original items (e.g., M. G. Rhodes & Anastasi, 2000; Thapar & McDermott, 2001). It has been also demonstrated that when to-be-remembered items are related categorically, participants often produce false alarms by erroneously recognizing critical lures that are nonpresented members of studied categories (Koutstaal & Schacter, 1997). It is also known that focusing on perceptual details of pictorially presented information leads to more accurate recognition (Marks, 1991). Although hits in this case might be slightly lower, false alarms are significantly lower than when participants are engaged in deep semantic processing. Collectively, these findings suggest that identification of an item's category (which is a variant of deeper semantic processing) would result in a higher level of memory intrusions and thus in lower recognition accuracy than shallow perceptual processing (see also Brainerd Reyna, & Forrest, 2002, for related arguments).

Thus, a memory test administered after an induction task may reveal differential encoding of information during induction: If participants perform category-based induction, they should be engaged in deep semantic processing, and therefore exhibit low discrimination of studied items from critical lures during a memory test (compared to a no-induction baseline condition). On the other hand, if participants perform similarity-based induction, they should be engaged in shallow perceptual processing, and, as a result, their memory accuracy should not decrease compared to the baseline. Because young children, unlike adults, were expected to perform similarity-based induction, this reasoning led to a nontrivial prediction that after performing induction, young children may exhibit greater memory accuracy (i.e., have fewer false alarms) than adults.

These predictions have received empirical support: The pattern of results reported by Sloutsky and Fisher (2004a, 2004b) indicates that while adults perform category-based induction, young children perform similarity-based induction. In particular, after performing inductive generalizations about members of familiar animal categories (i.e., cats, bears, and birds), adults' memory accuracy attenuated markedly compared to the no-induction baseline. At the same time, young children were accurate in both the baseline and induction conditions, exhibiting greater accuracy in the induction condition than adults. However, after providing short training on category-based induction (participants were taught that things that have the same name belong to the same kind and have much in common), memory accuracy of 5-year-olds decreased to the level of adults in the induction condition. At the same time, training did not attenuate children's accuracy in the baseline condition. That is, even after training, 5-year-olds exhibited high accuracy on recognition memory tasks. These findings suggest that the decrease in memory accuracy observed in the induction condition is attributable to the specific effects of training to perform category-based induction rather than to general factors such as fatigue. These results demonstrate that young children (unlike adults) spontaneously perform induction in a similarity-based rather than category-based manner and that they can learn to perform category-based induction via simple training. In a subsequent study, Fisher and Sloutsky (2005) demonstrated that category-based induction undergoes protracted development, with recognition memory accuracy dropping to the level of adults only by 11 years of age (Figure 12.13). The development of category-based induction is inferred from the semantic interference effect, that is, from lower memory in the induction condition than in the baseline condition.

Another way of examining the process of inductive inference was suggested by Sloutsky, Kloos, and Fisher (2007), who gave participants direct access to category information by teaching them a new natural-kind category that had a clear category-identification rule. Once participants had learned the category, they were presented with an induction task, in which category membership was pitted against appearance. If, for natural kinds, category-based induction is the default, then young children (who successfully learn the category) should assume that members of

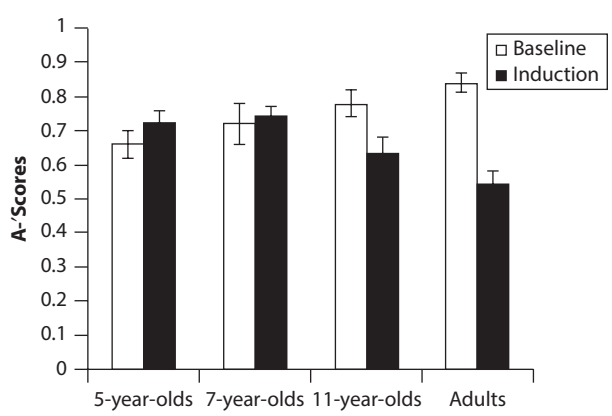


**Figure 12.13** The development of category-based induction after Fisher and Sloutsky (2005).

the same kind have much in common. As a result, when performing induction, they should rely on category membership and ignore appearance information. Conversely, if similarity-based induction is the default, then young children (even when they successfully learn the category) should rely on appearance information, while disregarding category membership information.

In the experiments reported by Sloutsky et al. (2007), 4- to 5-year-olds were first presented with a category learning task during which they learned that artificial animal-like creatures belong to two natural kinds: nice, friendly pets or wild, dangerous animals. The membership in a category could be detected by a rule, whereas appearances were not predictive of category membership. Children were then given a categorization task with items that differed from those used during training. Participants readily acquired these categories and accurately sorted the items according to their kind information. Then participants were presented with a triad induction task. Each triad consisted of a target and two test items, with one test item sharing the target's category membership but not its appearance, and the other test item sharing the target's appearance but not its category membership. Participants were familiarized with a quasi-biological property of the target, and asked to generalize this property to one of the test items. Finally, participants were given a final (i.e., postinduction) categorization task using the same items as in the induction task. The results provided little support for category-based induction early in development: 4- to 5-year-olds successfully learned the categories, but generalized properties on the basis of common appearance (Figure 12.14).

One potential criticism of this research is that the researchers failed to communicate conceptual information to young children. As a result, children might have interpreted these categories as artificial groupings rather than natural kinds that support inductive inference. There are several reasons to believe that this criticism is wrong. First, Sloutsky et al. (2007) communicated the biological relevance of the category-defining information and consistently referred to the studied categories as "kinds of animals." More importantly, there are published data by Gelman and Davidson (2013) that adults based their induction on these categories. Therefore, at least for adults, the description did suggest that the categories were natural kinds. However, it is also possible that while information provided by the researchers was sufficient for adults to infer that the studied categories were natural kinds, it was not sufficient for young children. Gelman and Davidson (2013) addressed this possibility by making every effort to communicate to young children that the categories were indeed natural kinds. They found that under these conditions 4- to 5-year-olds did perform category-based induction with the newly learned categories. However, Gelman and Davidson (2013) changed many other aspects of the original study as well (e.g., they made the category-defining information highly salient and used a training regime that could have attracted attention to this highly salient information). It is therefore possible that these manipulations rather than conceptual information directed children's attention to category-defining information such that they subsequently used this information in their induction. Overall, the extent to which preschoolers are capable of category-based induction remains an open question.

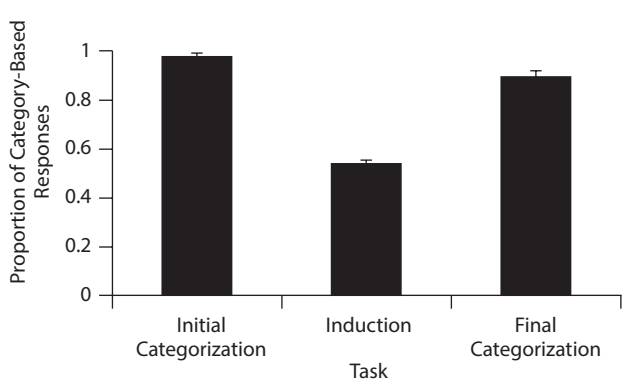


**Figure 12.14** Proportions of category-based responses by task in Sloutsky et al. (2007).

### *The Development of Inductive Inference*

Many models of inductive inference view generalization as the result of computing the overlap or similarity between the features of the premise (or inductive base) and the conclusion (e.g., Osherson, Smith, Wilkie, López, & Shafir, 1990; Sloman, 1993; Sloutsky & Fisher, 2004a). Therefore, whether the items are presented as pictures or as verbal arguments, people are generally more likely to generalize a property from a robin to a blue jay than from a robin to a monkey. Although most researchers agree that premise-conclusion similarity is important, some argue that category information is important as well. For example, Osherson et al. (1990) in their influential Similarity-Coverage model of induction focused on two components that potentially guide induction: the similarity component (which reflected the premise-conclusion similarity) and the coverage component. The coverage component focuses on how well the premise category covers the conclusion category. For example, in the argument "Mice and bears have an ulnary artery, therefore mammals

have an ulnary artery," premise categories (i.e., mice and bears) provide broad coverage of the conclusion category (i.e., mammal). In contrast, in the argument "Mice and rats have an ulnary artery, therefore mammals have an ulnary artery," premise categories provide narrow coverage of the conclusion category.

There are several phenomena that are diagnostic of the coverage component, with *monotonicity* and *diversity* being most extensively studied in developmental literature. Monotonicity reflects the effect of sample size on induction. For example, the inference from *robins*, *eagles*, and *sparrows* to *birds* is stronger than the inference from *robins* to *birds*. Diversity reflects the effect of sample variability on induction. For example, the inference from *robins*, *falcons*, and *chicken* to *birds* is stronger than the inference from *eagles*, *hawks*, and *falcons* to *birds*. The coverage component seems to reflect the extent to which induction is category based. What is the developmental time course of category-based induction as reflected in the development of the coverage component?

A number of studies (e.g., Gutheil & Gelman, 1997; López, Gelman, Gutheil, & E. E. Smith, 1992; M. Rhodes, Gelman, & Brickman , 2010) focused on monotonicity and diversity in an attempt to examine the development of category-based induction. The results indicate that although adults make use of information concerning sample size (larger samples are a stronger basis of inference than are smaller samples) and sample diversity (more diverse samples are better than more homogeneous samples) when making inductive judgments, children do not do so until age 8 or 9 and even then to only a limited degree. These results converge with findings (e.g., Fisher & Sloutsky, 2005) suggesting a protracted development of category-based induction.

However, there are a number of studies suggesting that the development of the coverage component may occur earlier than previously believed. In one study, M. Rhodes et al. (2010) compared sensitivity to sample diversity in 5-year-olds and adults under two conditions. In the *expert* condition, properties of the premise animals were communicated by an expert (a character who was introduced as knowing a lot about animals), whereas in the *novice* condition, these properties were communicated by a novice character who was introduced as having discovered these properties. In addition, in contrast to the previous research, both premise and conclusion categories were instantiated with pictures. Therefore, a nondiverse premise set included pictures of three Dalmatians and the conclusion was a picture of a collie. In contrast, a diverse premise set included a Dalmatian, a golden retriever, and a basset hound, and the conclusion was again the collie. Surprisingly, in the expert condition, 5-year-olds were very similar to adults in that they were much more likely to generalize on the basis of a diverse sample. However, in the novice condition, 5-year-olds exhibited an unexpected pattern (see Figure 12.15): Although 5-year-olds' reliance on diverse arguments did not decrease, their reliance on nondiverse arguments increased dramatically. These are provocative findings and they raise several questions. First, given relatively strong reliance on diverse premises in both expertise conditions and given that the premises were instantiated with pictures, it is possible that many premise pictures merely increase premise conclusion similarity compared to the previous studies. And second, why did the novice condition result in increased reliance on nondiverse premises?

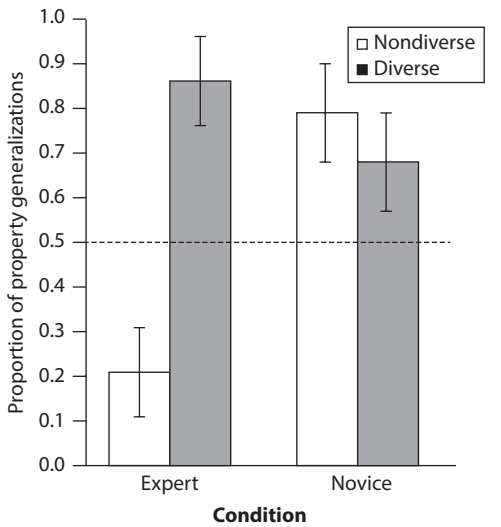


**Figure 12.15** Proportions of property generalizations to basic-level matches, by condition and sample in 5-year-olds, after M. Rhodes et al. (2010).

In another study, Hayes and Thompson (2007) examined the development of sensitivity to potentially causal relations between a premise feature and conclusion feature (e.g., has large eyes → can see in the dark). Obviously, reliance on a causal connection between the premise and conclusion category is a more advanced form of inductive inference than reliance on similarity. Children (aged 5, 8, and 9 years) and college undergraduates were presented with two new categories, Waddo and Xoxney, and a description of each category. The description included three features, such that two features that had a potential causal connection (e.g., "has large eyes" and "can see

in the dark"), whereas the third feature was unrelated to the other two (e.g., "has white wings"). Then participants were presented with an induction test in which the target was described as having a causal feature of Waddo (e.g., "has large eyes") and a noncausal feature of Xoxney (e.g., "has a long beak"). Participants were then asked if the target could see in the dark like Waddo or jump high like Xoxney. It was reasoned that if participants understand the causal connection they should systematically select Waddo; otherwise their responding would be at chance. The results indicated that when causal information was made explicit, even 5-year-olds were above chance in relying on it. However, when it was not made explicit, even 8- to 9-year-olds were at chance. Therefore, it is not clear what drives the effects: Is it causal relatedness or is it any link between or among features? Fortunately, the authors addressed this question in a separate experiment in which they first explicated causal relations (e.g., "they have *large eyes* to *better see in the dark*") as well as noncausal temporal relations (e.g., "they *touch the bark* when they *eat leaves from trees*"). They then pitted a causal feature ("has large eyes") and a noncausal feature ("touch the bark") and asked to predict whether it sees in the dark like Waddo or eat leaves from trees like Xoxney. In this condition, 5-year-olds were at chance, whereas older children and adults tended to rely on causal features. This research suggests that 5-year-olds rely on any correlated features, whereas 8- to 9-year-olds rely on causally related features. Therefore, reliance on deeper properties and theoretically important relations in the course of induction is a result of protracted development. Although the factors contributing to these developments are not known, given how protracted the development is, it is likely that formal education is a contributing factor. However, this is merely a conjecture and extensive research is needed to evaluate this hypothesis.

### Summary

Concepts undergo dramatic development after infancy. First, there are developments that are likely to be attributed to more general cognitive development, including the development of attention and memory. In particular, due to development of selective attention, children develop the ability to acquire increasingly sparse categories, thus becoming less dependent on similarity and within-category featural overlap. Second, language coupled and formal instruction become important sources of conceptual development, with many concepts (e.g., *love*, *matter*, or *number*) originating in language and some of these concepts requiring formal instruction. Furthermore, acquisition of quantifiers may contribute to the development of mastery of class-inclusion relations, whereas increasing lexical knowledge subserves the formation of conceptual networks (e.g., Landauer & Dumais, 1997). Third, there is evidence of a semantic development, with concepts forming conceptual networks of increasing within-network coherence and between-network differentiation. These networks may give rise to knowledge domains, reflecting the structure (taxonomical or otherwise) of these domains. And finally, conceptual networks give rise to category-based inference, supplementing the earlier emerging ability to perform inductive generalization on the basis of similarity. Each of these developments is likely to involve different processes and mechanisms, and the goal of future research is to uncover these processes and mechanism.

## PRINCIPLES OF CONCEPTUAL DEVELOPMENT

Although the study of concepts and their development has over a 2,000-year history, our understanding of conceptual development is vastly incomplete. Despite general agreement that (a) conceptual behaviors are diverse, (b) some of them exhibit early onset and are present in multiple species, and (c) multiple processes contribute to conceptual development, our understanding of precise developmental, cognitive, and brain mechanisms of conceptual behavior is incomplete. With that in mind, I will try to formulate the most general principles of conceptual development.

### Principle 1: The Diversity of Conceptual Behaviors

As indicated in this review, there are multiple forms of conceptual behavior ranging from relatively simple and universal (e.g., the ability to generalize) to relatively complex, uniquely human ones (e.g., the ability to form abstract concepts, conceptual networks, and structurally organized domains of knowledge). The simpler forms may establish the foundation for the more complex ones.

### Principle 2: Simpler Forms Are More Universal; Complex Forms Are More Unique

Simpler forms of conceptual behavior are more universal: They exhibit early onset and a relatively shallow developmental curve. They also present in a variety of species.

In contrast, more complex forms are likely to be uniquely human: They exhibit later onset and marked development. In addition, more complex forms of conceptual behavior are likely to depend on other aspects of cognitive development, including the development of attention and memory.

### Principle 3: Complex Forms of Conceptual Behavior Are Likely to Be Affected by Language and Instruction

Whereas simpler forms of conceptual behavior are independent of language or instruction—as demonstrated by the ability of nonlinguistic organisms (animals and prelinguistic infants) to perform these behaviors—the more advanced forms of conceptual behavior may depend critically on language and instruction. Language is particularly important for acquisition of abstract concepts denoting unobservable or even fictitious entities and for the development of conceptual networks. Some of these abstract concepts may also require instruction. For example, it is difficult to imagine how scientific, mathematical, or legal concepts and conceptual networks within these domains can be acquired without both language and instruction. Although language and instruction may not be sufficient for acquiring these concepts, both seem to be necessary.

### Principle 4: The Structure of Input Matters

In learning of new categories, the structure of input matters: Categories that are based on multiple featural overlap (and thus statistically dense) are easier to learn without instruction than are categories that are based on few defining features. Therefore, learning of statistically denser categories exhibits early onset, is present in a broad variety of species, and does not require instruction. In contrast, learning of more statistically sparse categories exhibits later onset, may be limited to organisms with a functioning prefrontal cortex, and may require instruction. Also, as has been shown by computational work (e.g., Hills et al., 2009; Landauer & Dumais, 1997), structure may also stem from language, especially for those concepts that lack perceptual structure.

### Principle 5: Conceptual Development Progresses From Less Structured Representations to More Structured Representations

Many of the early appearing, simpler conceptual behaviors are based on similarity or featural overlap among the to-be-grouped entities. Therefore, although structure transpires across the entities (in that they have features in common), there is little structure across the categories. At the same time, semantic development may include the development of conceptual networks (and possibly domains of knowledge), with increasing coherence in relations within the network, and greater distinction among the networks.

## CONCLUDING COMMENTS: FUTURE OF RESEARCH ON CONCEPTUAL DEVELOPMENT

Given the long history of research on conceptual development, it is useful to ask, Where is the field now and where it is going? Although the ability of humans to acquire and use concepts of various degrees of complexity is well established, the origins of this ability, its ontogenesis, and its neurobiology are not well understood. Therefore, our remaining challenge is to understand the links among developmental, cognitive, and brain processes of conceptual behaviors, thus developing a deeper, more complete understanding of the ability so central for our intelligence. Three issues seem to be critical in our understanding of concepts and their development: structure and mechanism, development, and biological foundations.

### Structure and Mechanism

One of the major challenges in understanding conceptual development is to develop a more complete knowledge of how concepts are learned, represented, and integrated into interconnected structures and then, in turn, how individual concepts and parts of the structure are used in reasoning and problem solving. At present, we have a variety of theories of category learning and a variety of theories of conceptual structure, but no integrated theoretical framework. Developing such a framework would substantially advance our understanding of conceptual behaviors and conceptual development.

### Development

Although what children can and cannot do at different ages is relatively well documented, the developmental process itself is not well understood. That is, it is not well understood what processes underlie the observed age differences or how changes in these processes transform the performance of a younger child into that of an

older child. Of course, it is also possible (albeit unlikely) that conceptual development is more simply a function of knowledge acquisition; If so, age-related differences may merely reflect differences in underlying knowledge. One of the most interesting challenges is therefore to link conceptual development with developmental changes in the underlying processes or with age-related increases in knowledge.

### Biological Foundations

Another critical challenge in understanding conceptual development is to link both mechanism and development with biological processes, particularly with brain functioning and development. Such a link may provide additional evidence on how concepts are learned and represented and how these representations change in the course of development. Understanding biological foundations of conceptual development may also shed light on an important yet often neglected problem—the nature of individual differences in conceptual development.

space is needed

To return to the arguments that opened this chapter, people do not exhibit evidence of conceptual knowledge at birth; therefore, one of the most interesting and exciting challenges in the study of human cognition is to understand how people acquire conceptual knowledge in the course of development and learning. Although some general principles of conceptual development can be formulated, the field has yet to meet the challenge and develop a comprehensive theory of conceptual development. Future research revealing the biological and psychological processes underlying conceptual development will move us closer to this goal.

## REFERENCES


Alvarado, M. C., & Bachevalier, J. (2000). Revisiting the maturation of medial temporal lobe memory functions in primates. *Learning & Memory, 7*, 244–256.

Anderson, J. R. (1991). The adaptive nature of human categorization. *Psychological Review, 98*, 409–429.

Ashby, F. G., & Maddox, W. T. (2005). Human category learning. *Annual Review of Psychology, 56*, 149–178.

Ashby, F. G., Alfonso-Reese, L., Turken, A., & Waldron, E. (1998). A neuropsychological theory of multiple systems in category learning. *Psychological Review, 105*, 442–481.

Balaban, M. T., & Waxman, S. R. (1997). Do words facilitate object categorization in 9-month-old infants? *Journal of Experimental Child Psychology, 64*, 3–26.

Bar-Gad, I., Morris, G., & Bergman, H. (2003). Information processing, dimensionality reduction and reinforcement learning in the basal ganglia. *Progress in Neurobiology, 71*, 439–473.

Barnes, J. (1995, Ed.). *Complete works of Aristotle*. Princeton, NJ: Princeton University Press.

Barsalou, L.W. (1999). Perceptual symbol systems. *Behavioral and Brain Sciences, 22*, 577-609.

Behl-Chadha, G. (1996). Basic-level and superordinate-like categorical representations in early infancy. *Cognition, 60*, 105–141.

Berg, E. A. (1948). A simple objective test for measuring flexibility and thinking. *Journal of General Psychology, 39*, 15–22.

Bhatt, R. S., & Quinn, P. C. (2010). How does learning impact development in infancy? The case of perceptual organization. *Infancy, 16*, 2–38.

Bhatt, R. S., Wasserman, E. A., Reynolds, W. F., & Knauss, K. S. (1988). Conceptual behavior in pigeons: Categorization of both familiar and novel examples from four classes of natural and artificial stimuli. *Journal of Experimental Psychology: Animal Behavior Processes, 14*, 219.

Blair, M. R., Watson, M. R., & Meier, K. M. (2009). Errors, efficiency, and the interplay between attention and category learning. *Cognition, 112*, 330–336.

Blewitt, P. (1983). Dog versus Collie: Vocabulary in speech to young children. *Developmental Psychology, 19*, 602–609.

Bomba, P. C., & Siqueland, E. R. (1983). The nature and structure of infant form categories. *Journal of Experimental Child Psychology, 35*, 294–328.

Booth, A. E., & Waxman, S. R. (2009). A horse of a different color: Specifying with precision infants' mappings of novel nouns and adjectives. *Child Development, 80*, 15–22.

Borges, J. L. (1962). Funes the memorious. In A. Kerrigan (Ed. & Trans.), *Ficciones* (pp. 107–115). New York, NY: Grove Press. (Original work published 1942)

Brainerd, C. J., Reyna, V. F., & Forrest, T. J. (2002). Are young children susceptible to the false-memory illusion? *Child Development, 73*, 1363–1377.

Brown, R. G., & Marsden, C. D. (1990). Cognitive function in Parkinson's disease: From description to theory. *Trends in Neurosciences, 13*, 21-29.

Buffalo, E. A., Ramus, S. J., Clark, R. E., Teng, E., Squire, L. R., & Zola, S. M. (1999). Dissociation between the effects of damage to perirhinal cortex and area TE. *Learning & Memory, 6*, 572–599.

Bunge, S. A., & Zelazo, P. D. (2006). A brain-based account of the development of rule use in childhood. *Current Directions in Psychological Science, 15*, 118–121.

Callanan, M. A. (1985). How parents label objects for young children: The role of input in the acquisition of category hierarchies. *Child Development, 56*, 508–523.

Callanan, M. A. (1989). Development of object categories and inclusion relations: preschoolers' hypotheses about word meanings. *Developmental Psychology, 25*, 207–216.

Carey, S. (1985). *Conceptual change in childhood*. Cambridge, MA: MIT Press.

Carlson, S. M. (2005). Developmentally sensitive measures of executive function in preschool children. *Developmental Neuropsychology, 28*, 595–616.

Casasola, M., & Bhagwat, J. (2007). Do novel words facilitate 18-month-olds"spatial categorization? *Child Development, 78*, 1818–1829.

Casasola, M., Bhagwat, J., & Burke, A. S. (2009). Learning to form a spatial category of tight-fit relations: How experience with a label can give a boost. *Developmental Psychology, 45*, 711–723.

Caviness, V. S., Kennedy, D. N., Richelme, C., Rademacher, J., & Filipek, P. A (1996). The human brain age 7–11 years: A volumetric analysis based on magnetic resonance images. *Cerebral Cortex, 6*, 726–736.

Chi, M. T. H., Hutchinson, J. E., & Robin, A. F. (1989). How inferences about novel domain-related concepts can be constrained by structured knowledge. *Merrill-Palmer Quarterly, 35*, 27–62.

Cimpian, A., & Erickson, L. C. (2012). Remembering kinds: New evidence that categories are privileged in children's thinking. *Cognitive Psychology, 64*, 161–185.

Cimpian, A., & Markman, E. M. (2009). Information learned from generic language becomes central to children's biological concepts: Evidence from their open-ended explanations. *Cognition, 113*, 14–25.

Cimpian, A., & Park, J. J. (2013). Tell me about pangolins! Evidence that children are motivated to learn about kinds. *Journal of Experimental Psychology: General*. Advance online publication. doi: 10.1037/a0031687

Cimpian, A., & Scott, R. M. (2012). Children expect generic knowledge to be widely shared. *Cognition, 123*, 419–433.

Cincotta, C. M., & Seger, C. A. (2007). Dissociation between striatal regions while learning to categorize via feedback and via observation. *Journal of Cognitive Neuroscience, 19*, 249–265.

Cohen, L. B., & Cashon, C. H. (2006). Infant cognition. In D. Kuhn & R. S. Siegler (Eds.), Cognition, perception, and language. *Volume 2 of the* Handbook of child psychology (pp. 214–251) (6th ed.). Editors-in-Chief: W. Damon & R. M. Lerner. Hoboken, NJ: Wiley.

Collins, A. M., & Quillian, M. R. (1969). Retrieval time from semantic memory. *Journal of Verbal Learning and Verbal Behavior, 8*, 240–247.

Colunga, E., & Smith, L. B. (2005). From the lexicon to expectations about kinds: A role for associative learning. *Psychological Review, 112*, 347.

Cools, A. R., van den Bercken, J. H. L., Horstink, M. W. I., van Spaendonck, K. P. M., & Berger, H. J. C. (1984). Cognitive and motor shifting aptitude disorder in Parkinson's disease. *Journal of Neurology, Neurosurgery and Psychiatry, 47*, 443–453.

Cook, R. G., Katz, J. S., & Cavoto, B. R. (1997). Pigeon same—different concept learning with multiple stimulus classes. *Journal of Experimental Psychology: Animal Behavior Processes, 23*, 417–433.

Cowan, N. E. (1997). *The development of memory in childhood*. Hove, England: Psychology Press/Erlbaum.

Craik, F. I., & Lockhart, R. S. (1972). Levels of processing: A framework for memory research. *Journal of Verbal Learning and Verbal Behavior, 11*, 671–684.

Craik, F. I., & Tulving, E. (1975). Depth of processing and the retention of words in episodic memory. *Journal of Experimental Psychology: General, 104*, 268–294.

Dale, P. S., & Fenson, L. (1996). Lexical development norms for young children. *Behavior Research Methods, Instruments, & Computers, 28*, 125–127.

Davidson, M. C., Amso, D., Anderson, L. C., & Diamond, A. (2006). Development of cognitive control and executive functions from 4 to 13 years: Evidence from manipulations of memory, inhibition, and task switching. *Neuropsychologia, 44*, 2037–2078.

Deng, W., & Sloutsky, V. M. (2012). Carrot eaters or moving heads: Inductive inference is better supported by salient features than by category labels. *Psychological Science, 23*, 178–186.

Diamond, A. (2002). Normal development of prefrontal cortex from birth to young adulthood: Cognitive functions, anatomy, and biochemistry. In D. T. Stuss & R. T. Knight (Eds.), *Principles of frontal lobe function* (pp. 466–503). London, England: Oxford University Press.

Diamond, A., & Goldman-Rakic, P. S. (1989). Comparison of human infants and rhesus monkeys on Piaget's AB task: Evidence for dependence on dorsolateral prefrontal cortex. *Experimental Brain Research, 74*, 24–40.

Eimas, P. D. (1994). Categorization in early infancy and the continuity of development. *Cognition, 50*, 83–93.

Eimas, P. D., & Quinn, P. C. (1994). Studies on the formation of perceptually based basic-level categories in young infants. *Child Development, 65*, 903–917.

Fan, J., McCandliss, B. D., Sommer, T., Raz, A., & Posner, M. I. (2002). Testing the efficiency and independence of attentional networks. *Journal of Cognitive Neuroscience, 14*, 340–347.

Fenson, L., Dale, P. S., Reznick, J. S., Bates, E., Thal, D. J., & Pethick, S. J. (1994). Variability in early communicative development. *Monographs of the Society for Research in Child Development, 59*, 1–173.

Fernandez-Ruiz, J., Wang, J., Aigner, T. G., & Mishkin, M. (2001). Visual habit formation in monkeys with neurotoxic lesions of the ventrocaudal neostriatum. *Proceedings of the National Academy of Sciences, 98*, 4196–4201.

Fisher, A. V. (2010). What's in the name? Or how rocks and stones are different from bunnies and rabbits. *Journal of Experimental Child Psychology, 105*, 198–212.

Fisher, A. V., & Sloutsky, V. M. (2005). When induction meets memory: Evidence for gradual transition from similarity-based to category-based induction. *Child Development, 76*, 583–597.

Fisher, A. V., Matlen, B. J., & Godwin, K. E. (2011). Semantic similarity of labels and inductive generalization: Taking a second look. *Cognition, 118*, 432–438.

Flavell, J. H. (1970). Concept development. In Paul H. Mussen (Ed.), *Carmichael's manual of child psychology* (Vol. *1*, pp. 983–1059). New York, NY: Wiley.

Fodor, J. (1972). Some reflections on LS Vygotsky's Thought and Language. *Cognition, 1*, 83–95.

French, R. M., Mareschal, D., Mermillod, M., & Quinn, P. C. (2004). The role of bottom-up processing in perceptual categorization by 3- to 4-month-old infants: Simulations and data. *Journal of Experimental Psychology: General, 133*, 382–397.

Fulkerson, A. L., & Haaf, R. A. (2003). The influence of labels, nonlabeling sounds, and source of auditory input on 9- and 15-month-olds' object categorization. *Infancy, 4*, 349–369.

Gelman, S. A. (2003). *The essential child: Origins of essentialism in everyday thought*. New York, NY: Oxford University Press.

Gelman, S. A. (2004). Psychological essentialism in children. *Trends in Cognitive Sciences, 8*(9), 404–409.

Gelman, S. A., & Coley, J. (1991). Language and categorization: The acquisition of natural kind terms. In S. A. Gelman, S. & J. P. Byrnes (Eds.), *Perspectives on language and thought: Interrelations in development* (pp. 146–196). New York, NY: Cambridge University Press.

Gelman, S. A., & Davidson, N. S. (2013). Conceptual influences on category-based induction. *Cognitive Psychology, 66*, 327–353.

Gelman, S. A., & Kalish, C. W. (2006). Conceptual development. In D. Kuhn & R. Siegler (Eds.), Cognition, perception, and language. *Volume 2 of the* Handbook of child psychology (pp. 687–733) (6th ed.). Editors-in-Chief: W. Damon & R. M. Lerner. Hoboken, NJ: Wiley.

Gelman, S. A., & Markman, E. M. (1986). Categories and induction in young children. *Cognition, 23*, 183–209.

Gentner, D. (1981). Some interesting differences between nouns and verbs. *Cognition and Brain Theory, 4*, 161–178.

Gentner, D., & Kurtz, K. J. (2005). Relational categories. In W. K. Ahn, R. L. Goldstone, B. C. Love, A. B. Markman, & P. W. Wolff (Eds.), *Categorization inside and outside the lab* (pp. 151–175). Washington, DC: American Psychological Association.

Ghetti, S., & Lee, J. (2010). Children's episodic memory. *Wiley Interdisciplinary Reviews: Cognitive Science, 2*, 365–373.

Giedd, J. N., Snell, J. W., Lange, N., Rajapakse, J. C., Casey, B. J., Kozuch, P. L., … Rapoport, J. L. (1996). Quantitative magnetic resonance imaging of human brain development: Ages 4–18. *Cerebral Cortex, 6*, 551–560.

Gliga, T., Volein, A., & Csibra, G. (2010). Verbal labels modulate perceptual object processing in 1-year-old children. *Journal of Cognitive Neuroscience, 22*, 2781–2789.

Gliozzi, V., Mayor, J., Hu, J.-F., & Plunkett, K. (2009). Labels as features (not names) for infant categorization: A neurocomputational approach. *Cognitive Science, 33*, 709–738.

Goldstone, R. L. (1994). The role of similarity in categorization: Providing a groundwork. *Cognition, 52*, 125–157.

Graham, S. A., & Kilbreath, C. S. (2007). It's a sign of the kind: Gestures and words guide infants' inductive inferences. *Developmental Psychology, 43*, 1111–1123.

Greene, T. R. (1994). What kindergartners know about class inclusion hierarchies. *Journal of Experimental Child Psychology, 57*, 72–88.

Gutheil, G., & Gelman, S. A. (1997). Children's use of sample size and diversity information within basic-level categories. *Journal of Experimental Child Psychology*, *64*, 159–174.

Halford, G. S., Andrews, G., & Jensen, I. (2002). Integration of category induction and hierarchical classification: One paradigm at two levels of complexity. *Journal of Cognition and Development, 3*, 143–177.

Hammer, R., Diesendruck, G., Weinshall, D., & Hochstein, S. (2009). The development of category learning strategies: What makes the difference? *Cognition, 112*, 105–119.

Hanania, R., & Smith, L. B. (2009). Selective attention and attention switching: Towards a unified developmental approach. *Developmental Science, 13*, 622–635.

Hatano, G., & Inagaki, K. (1994). Young children's naive theory of biology. *Cognition, 50*, 171–188.

Hayes, B. K., & Heit, E. (2004). Why learning and development can lead to poorer recognition memory. *Trends in Cognitive Sciences, 8*, 337–339.

Hayes, B. K., & Thompson, S. P. (2007). Causal relations and feature similarity in children's inductive reasoning. *Journal of Experimental Psychology: General, 136*, 470-484.

Hayne, H. (1996). Categorization in infancy. *Advances in Infancy Research, 10*, 79–120.

Hayne, H. (2004). Infant memory development: Implications for childhood amnesia. *Developmental Review, 24*, 33–73.

Herrnstein, R. J., & Loveland, D. H. (1964). Complex visual concept in the pigeon. *Science*, *146*, 549–550.

Hills, T. T., Maouene, M., Maouene, J., Sheya, A., & Smith, L. (2009). Categorical structure among shared features in networks of early-learned nouns. *Cognition, 112*, 381–396.

Homa, D., Rhoades, D., & Chambliss, D. (1979). Evolution of conceptual structure. *Journal of Experimental Psychology: Human Learning and Memory, 5*, 11–23.

Humphreys, G. W., & Forde, E. M. (2001). Hierarchies, similarity, and interactivity in object recognition: "Category-specific" neuropsychological deficits. *Behavioral and Brain Sciences, 24*, 453–476.

Inagaki, K., & Hatano, G. (2002). *Young children's naive thinking about biological world*. New York, NY: Psychology Press.

Inhelder, B., & Piaget, J. (1964). *The early growth of logic in the child: Classification and seriation*. New York, NY: Harper & Row.

James, W. (1983). *The principles of psychology*. Cambridge, MA: Harvard University Press. (Original work published 1890)

Japkowicz, N. (2001). Supervised versus unsupervised binary-learning by feedforward neural networks. *Machine Learning, 42*, 97–122.

Keates, J., & Graham, S. A. (2008). Category markers or attributes: Why do labels guide infants' inductive inferences? *Psychological Science, 19*, 1287–1293.

Keil, F. C. (1981). Constraints on knowledge and cognitive development. *Psychological Review, 88*, 197–227.

Kemp, C. (2012). Exploring the conceptual universe. *Psychological Review, 119*, 685–722.

Kemp, C., Shafto, P., & Tenenbaum, J. B. (2012). An integrated account of generalization across objects and features. *Cognitive Psychology, 64*, 35–73.

Kirkham, N. Z., Cruess, L., & Diamond, A. (2003). Helping children apply their knowledge to their behavior on a dimension-switching task. *Developmental Science, 6*, 449–467.

Kloos, H., & Sloutsky, V. M. (2008). What's behind different kinds of kinds: Effects of statistical density on learning and representation of categories. *Journal of Experimental Psychology: General, 137*, 52–72.

Knowlton, B. J., Mangels, J. A., Squire, L. R. (1996). A neostriatal habit learning system in humans. *Science, 273*, 1399–1402.

Koutstaal, W., & Schacter, D. L. (1997). Gist-based false recognition of pictures in older and younger adults. *Journal of Memory and Language, 37*, 555–583.

Koutstaal, W., Wagner, A. D., Rotte, M., Maril, A., & Buckner, R. L. (2001). Perceptual specificity in visual object priming: Functional magnetic resonance imaging evidence for a laterality difference in fusiform cortex. *Neuropsychologia, 39*, 184–199

Kripke, S. (1972). Naming and necessity. In D. Davidson & G. Harman (Eds.), *Semantics of Natural Language* (pp. 253–355). Dordrecht, The Netherlands: Reider.

Kruschke, J. K. (1992). ALCOVE: An exemplar-based connectionist model of category learning. *Psychological Review, 99*, 22–44.

Kruschke, J. K. (1993). Human category learning: Implications for back-propagation models. *Connection Science, 5*, 3–36.

Kruschke, J. K. (2001). Toward a unified model of attention in associative learning. *Journal of Mathematical Psychology, 45*, 812–863.

Landauer, T.K., & Dumaus, S. T. (1997). A solution to Plato's problem: The latent semantic analysis theory of acquisition, induction, and representation of knowledge. *Psychological Review*, *104*, 211–240.

Lazareva, O. F., & Wasserman, E. A. (2008). Categories and concepts in animals. In R. Menzel (Ed.), Learning theory and behavior. *Volume 1 of* Learning and memory: A comprehensive reference (pp. 197–226). Editor-in-Chief: J. Byne. Oxford, England: Elsevier.

Locke, J. (1888). *An essay concerning human understanding*. London: Ward, Lock & Company. (Original work published 1689)

Lombardi, W. J., Andreason, P. J., Sirocco, K. Y., Rio, D. E., Gross, R. E., Umhau, J. C., Hommer, D. W. (1999). Wisconsin Card Sorting Test performance following head injury: Dorsolateral fronto-striatal circuit activity predicts perseveration. *Journal of Clinical and Experimental Neuropsychology, 21*, 2–16.

Love, B. C., & Gureckis, T. M. (2007). Models in search of a brain. *Cognitive, Affective, & Behavioral Neuroscience, 7*, 90–108.

López, A., Gelman, S. A., Gutheil, G., & Smith, E. E. (1992). The development of category-based induction. *Child Development, 63*, 1070–1090.

Luciana, M., & Nelson, C. A. (1998). The functional emergence of prefrontally-guided working memory systems in four-to eight-year-old children. *Neuropsychologia, 36*, 273–293.

Lupyan, G., Rakison, D. H., & McClelland, J. L. (2007). Language is not just for talking: Redundant labels facilitate learning of novel categories. *Psychological Science, 18*, 1077–1083.

Mackintosh, N. J. (1975). A theory of attention: Variations in the associability of stimuli with reinforcement. *Psychological Review, 82*, 276–298.

Mahon, B. Z., & Caramazza, A. (2009). Concepts and categories: A cognitive neuropsychological perspective. *Annual Review of Psychology, 60*, 27–51.

Mandler, J. M. (1992). How to build a baby: II. Conceptual primitives. *Psychological Review, 99*, 587–587.

Mandler, J. M. (1999). Seeing is not the same as thinking: Commentary on "making sense of infant categorization." *Developmental Review, 19*, 297–306.

Mandler, J. M., & Bauer, P. J. (1988). The cradle of categorization: Is the basic level basic? *Cognitive Development, 3*, 247–264.

Mandler, J. M., & McDonough, L. (1996). Drinking and driving don't mix: Inductive generalization in infancy. *Cognition, 59*, 307–335.

Mandler, J. M., & McDonough, L. (1998). Studies in inductive inference in infancy. *Cognitive Psychology, 37*, 60–96.

Marks, W. (1991). Effects of encoding the perceptual features of pictures on memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 17*, 566–577.

Marr, D. (1982). *Vision: A computational investigation into the human representation and processing of visual information*. New York, NY: Henry Holt.

Martin, A. (2007). The representation of object concepts in the brain. *Annual Review of Psychology, 58*, 25–45.

Mather, E., & Plunkett, K. (2011). Same items, different order: Effects of temporal variability on infant categorization. *Cognition, 119*, 438–447.

Mayor, J., & Plunkett, K. (2010). A neurocomputational account of taxonomic responding and fast mapping in early word learning. *Psychological Review, 117*, 1–31.

McClelland, J. L., & Rogers, T. T. (2003). The parallel distributed processing approach to semantic cognition. *Nature Reviews Neuroscience, 4*, 310–322.

McDonough, L., & Mandler, J. M. (1998). Inductive generalization in 9- and 11-month-olds. *Developmental Science*, *1*, 227–232.

McMurray, B., & Aslin, R. N. (2004). Anticipatory eye movements reveal infants' auditory and visual categories. *Infancy, 6*, 203–229.

McRae, K., Cree, G. S., Seidenberg, M. S., & Mcnorgan, C. (2005). Semantic feature production norms for a large set of living and nonliving things. *Behavior Research Methods, 37*, 547–559.

Medin, D. L. (1989). Concepts and conceptual structure. *American Psychologist, 44*, 1469–1481.

Medin, D. L., & Schaffer, M. M. (1978). Context theory of classification learning. *Psychological Review, 85*, 207–238.

Merriman, W. E., Schuster, J. M., & Hager, L. (1991). Are names ever mapped onto preexisting categories? *Journal of Experimental Psychology: General, 120*, 288–300.

Mervis, C. B. (1987). Child-basic object categories and early lexical development. In U. Neisser (Ed.), *Concepts and Conceptual Development: Ecological and Intellectual Factors in Categorization*. New York, NY: Cambridge University Press.

Mill, J. S. (1843). A System of Logic *(2 vols)*. London, England: Parker.

Müller, U., & Overton, W. F. (1998). How to grow a baby: A reevaluation of image-schema and Piagetian action approaches to representation. *Human Development, 41*, 71–111.

Murphy, G. L. (2004). *The Big Book of Concepts*. Cambridge, MA: MIT Press.

Murphy, G. L., & Medin, D. L. (1985). The role of theories in conceptual coherence. *Psychological Review, 92*, 289–316.

Nagy, Z., Westerberg, H., & Klingberg, T. (2004). Maturation of white matter is associated with the development of cognitive functions during childhood. *Journal of Cognitive Neuroscience*, *16*, 1227–1233.

Nelson, C. A. (1995). The ontogeny of human memory. *Developmental Psychology*, *31*, 723–738.

Nelson, K. (1974). Concept, word, and sentence: Interrelations in acquisition and development. *Psychological Review, 81*, 267–285.

Newcombe, N. S., Lloyd, M. E., & Ratliff, K. R. (2007). Development of episodic and autobiographical memory: A cognitive neuroscience perspective. In R. V. Kail (Ed.), *Advances in child development and behavior* (Vol. *35*, pp. 40–89). London, England: Elsevier.

Nomura, E. M., & Reber, P. J. (2008). A review of medial temporal lobe and caudate contributions to visual category learning. *Neuroscience and Biobehavioral Reviews, 32*, 279–291.

Nosofsky, R. M. (1986). Attention, similarity, and the identification–categorization relationship. *Journal of Experimental Psychology: General, 115*, 39–57.

Nosofsky, R. M. (1988). Exemplar-based accounts of relations between classification, recognition, and typicality. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 14*, 700–708.

Oakes, L. M., Coppage, D. J., & Dingel, A. (1997). By land or by sea: The role of perceptual similarity in infants' categorization of animals. *Developmental Psychology, 33*, 396–407.

Opfer, J. E., & Siegler, R. S. (2004). Revisiting preschoolers' *living things* concept: A microgenetic analysis of conceptual change in basic biology. *Cognitive Psychology, 49*, 301–332.

Osherson, D. N., Smith, E. E., Wilkie, O., López, A., & Shafir, E. (1990). Category-based induction. *Psychological Review*, *97*, 185–200.

Pfefferbaum, A., Mathalon, D. H., Sullivan, E. V., Rawles, J. M., Zipursky, R. B., & Lim, K. O. (1994). A quantitative magnetic resonance imaging study of changes in brain morphology from infancy to late adulthood. *Archives of Neurology, 51*, 874–887.

Plude, D. J., Enns, J. T., & Brodeur, D. (1994). The development of selective attention: A life-span overview. *Acta Psychologica, 86*, 227–272.

Plunkett, K., Hu, J. F., & Cohen, L. B. (2008). Labels can override perceptual categories in early infancy. *Cognition, 106*, 665–681.

Posner, M. I., & Petersen, S. E. (1990). The attention system of the human brain. *Annual Review of Neuroscience, 13*, 25–42.

Quillian, M. R. (1967). Word concepts: A theory and simulation of some basic semantic capabilities. *Behavioral Science, 12*, 410–430.

Quine, W. V. (1960). *Word and Object*. Cambridge, MA: MIT Press.

Quinn, P. C. (1987). The categorical representation of visual pattern information by young infants. *Cognition, 27*, 145–179.

Quinn, P. C. (2002a). Beyond prototypes: Asymmetries in infant categorization and what they teach us about the mechanisms guiding early knowledge acquisition. In R. V. Kail & H. W. Reese (Eds.), *Advances in child development and behavior* (Vol. *29*, pp. 161–193). London, England: Elsevier.

Quinn, P. C. (2002b). Category representation in young infants. *Current Directions in Psychological Science, 11*, 66–70.

Quinn, P. C. (2011). Born to categorize. In U. Goswami (Ed.), *Blackwell handbook of childhood cognitive development* (pp. 129–152). Oxford, England: Blackwell.

Quinn, P. C., & Eimas, P. D. (1986). On categorization in early infancy. *Merrill-Palmer Quarterly, 32*, 331–363.

Quinn, P. C., Eimas, P. D., & Rosenkrantz, S. L. (1993). Evidence for representations of perceptually similar natural categories by 3-month-old and 4-month-old infants. *Perception, 22*, 463–463.

Quinn, P. C., & Johnson, M. H. (2000). Global-before-basic object categorization in connectionist networks and 2-month-old infants. *Infancy, 1*, 31–46.

Rakison, D. H., & Butterworth, G. E. (1998). Infants' use of object parts in early categorization. *Developmental Psychology, 34*, 49–62.

Rao, S. M., Bobholz, J. A., Hammeke, T. A., Rosen, A. C., Woodley, S. J., Cunningham, J. M., … Binder, J. R. (1997). Functional MRI evidence for subcortical participation in conceptual reasoning skills. *NeuroReport, 8*, 1987–1993.

Rhodes, M., Gelman, S. A., & Brickman, D. (2010). Children's attention to sample composition in learning, teaching and discovery. *Developmental Science, 13*(3), 421–429.

Rhodes, M. G., & Anastasi, J. S. (2000). The effects of a levels-of-processing manipulation on false recall. *Psychonomic Bulletin & Review, 7*, 158–162.

Richmond, J., & Nelson, C. A. (2007). Accounting for change in declarative memory: A cognitive neuroscience perspective. *Developmental Review, 27*, 349–373.

Rips, L. J., Shoben, E. J., & Smith, E. E. (1973). Semantic distance and the verification of semantic relations. *Journal of Verbal Learning and Verbal Behavior, 12*, 1–20.

Robinson, C. W., & Sloutsky, V. M. (2004). Auditory dominance and its change in the course of development. *Child Development, 75*, 1387–1401.

Robinson, C. W., & Sloutsky, V. M. (2007a). Linguistic labels and categorization in infancy: do labels facilitate or hinder? *Infancy, 11*, 233–253.

Robinson, C. W., & Sloutsky, V. M. (2007b). Visual processing speed: Effects of auditory input on visual processing. *Developmental Science*, *10*, 734–740.

Robinson, C. W., & Sloutsky, V. M. (2010). Effects of multimodal presentation and stimulus familiarity on auditory and visual processing. *Journal of Experimental Child Psychology, 107*, 351–358.

Rodman, H. R. (1994). Development of inferior temporal cortex in the monkey. *Cerebral Cortex, 4*, 484–498.

Rodman, H. R., Skelly, J. P., & Gross, C. G. (1991). Stimulus selectivity and state dependence of activity in inferior temporal cortex of infant monkeys. *Proceedings of the National Academy of Sciences, USA, 88*, 7572–7575.

Rogers, R. D., Andrews, T. C., Grasby, P. M., Brooks, D. J., & Robbins, T. W. (2000). Contrasting cortical and subcortical activations produced by attentional-set shifting and reversal learning in humans. *Journal of Cognitive Neuroscience, 12*, 142–162.

Rogers, T. T., Lambon Ralph, M. A., Garrard, P., Bozeat, S., McClelland, J. L., Hodges, J. R., & Patterson, K. (2004). Structure and deterioration of semantic memory: A neuropsychological and computational investigation. *Psychological Review, 111*, 205–235.

Rogers, T. T., & McClelland, J. L. (2004). *Semantic cognition: A parallel distributed processing approach*. Cambridge, MA: MIT Press.

Rosch, E., & Mervis, C. B. (1975). Family resemblances: Studies in the internal structure of categories. *Cognitive Psychology, 7*, 573–605.

Rosch, E., Mervis, C. B., Gray, W. D., Johnson, D. M., & Boyes-Braem, P. (1976). Basic objects in natural categories. *Cognitive Psychology, 8*, 382–439.

Rouder, J. N., & Ratcliff, R. (2004). Comparing categorization models. *Journal of Experimental Psychology: General, 133*, 63–82.

Rovee-Collier, C., Greco-Vigorito, C., & Hayne, H. (1993). The time-window hypothesis: Implications for categorization and memory modification. *Infant Behavior and Development, 16*, 149–176.

Rudy, J. W., Keith, J. R., & Georgen, K. (1993). The effect of age on children's learning of problems that require a configural association solution. *Developmental Psychobiology, 26*, 171–184.

Rueda, M., Fan, J., McCandliss, B. D., Halparin, J., Gruber, D., Lercari, L., & Posner, M. I. (2004). Development of attentional networks in childhood. *Neuropsychologia, 42*, 1029–1040.

Rumelhart, D. E., Hinton, G. E., & Williams, R. J. (1986). Learning internal representations by error propagation. In D. E. Rumelhart & J. L. McClelland (Eds.), *Parallel distributed processing* (pp. 318–362). Cambridge, MA: MIT Press.

Rumelhart, D. E., & Todd, P. M. (1993). Learning and connectionist representations. In E. D. Meyer & S. Kornblum (Eds.), *Attention and performance XIV: Synergies in experimental psychology, artificial intelligence, and cognitive neuroscience* (pp. 3–30). Cambridge, MA: MIT Press.

Samuelson, L. K., & Smith, L. B. (1998). Memory and attention make smart word learning: An alternative account of Akhtar, Carpenter, and Tomasello. *Child Development, 69*, 94–104.

Samuelson, L. K., & Smith, L. B. (1999). Early noun vocabularies: Do ontology, category structure and syntax correspond? *Cognition, 73*, 1–33.

Scribner, S., & Cole, M. (1973). Cognitive consequences of formal and informal education. *Science, 182*, 553–559.

Seger, C. A. (2008). How do the basal ganglia contribute to categorization? Their roles in generalization, response selection, and learning via feedback. *Neuroscience and Biobehavioral Reviews, 32*, 265–278.

Seger, C. A., & Cincotta, C. M. (2002). Striatal activity in concept learning. *Cognitive, Affective, & Behavioral Neuroscience, 2*, 149–161.

Seger, C. A., & Miller, E. K. (2010). Category learning in the brain. *Annual Review of Neuroscience, 33*, 203–219.

Shepard, R. N., Hovland, C. I., & Jenkins, H. M. (1961). Learning and memorization of classifications. *Psychological Monographs: General and Applied, 75*, 1–42.

Shipley, E. F. (1993). Categories, hierarchies, and induction. *Psychology of Learning and Motivation, 30*, 265–301.

Siegler, R., & Svetina, M. (2006). What leads children to adopt new strategies? *Child Development, 77*, 997–1015.

Simons, J. S., Koutstaal, W., Prince, S., & Wagner, A. D. (2003). Neural mechanisms of visual object priming: evidence for perceptual and semantic distinctions in fusiform cortex. *NeuroImage, 19*, 613–626.

Sloman, S. A. (1993). Feature-based induction. *Cognitive Psychology, 25*, 231–280.

Sloutsky, V. M. (2010). From perceptual categories to concepts: What develops? *Cognitive Science, 34*, 1244–1286.

Sloutsky, V. M., & Fisher, A. V. (2004a). Induction and categorization in young children: A similarity-based model. *Journal of Experimental Psychology: General, 133*, 166–188.

Sloutsky, V. M., & Fisher, A. V. (2004b). When development and learning decrease memory: Evidence against category-based induction in children. *Psychological Science, 15*, 553–558.

Sloutsky, V. M., & Fisher, A. V. (2012). Linguistic labels: Conceptual markers or object features? *Journal of Experimental Child Psychology, 111*, 65–86.

Sloutsky, V. M., Kloos, H., & Fisher, A. V. (2007). When looks are everything: Appearance similarity versus kind information in early induction. *Psychological Science, 18*, 179–185.

Sloutsky, V. M., & Lo, Y. F. (1999). How much does a shared name make things similar? Part 1. Linguistic labels and the development of similarity judgment. *Developmental Psychology, 35*, 1478–1492.

Sloutsky, V. M., Lo, Y.-F., & Fisher, A. V. (2001). How much does a shared name make things similar? Linguistic labels, similarity, and the development of inductive inference. *Child Development, 72*, 1695–1709.

Sloutsky, V. M., & Napolitano, A. C. (2003). Is a picture worth a thousand words? Preference for auditory modality in young children. *Child Development, 74*, 822–833.

Sloutsky, V. M., & Robinson, C. W. (2008). The role of words and sounds in infants' visual processing: From overshadowing to attentional tuning. *Cognitive Science, 32*, 342–365.

Sloutsky, V. M., & Robinson, C. W. (2013). Redundancy matters: Flexible learning of multiple contingencies in infants. *Cognition, 126*, 156–164.

Sluzenski, J., Newcombe, N. S., & Kovacs, S. L. (2006). Binding, relational memory, and recall of naturalistic events: A developmental perspective. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 32*, 89–100.

Smith, E. E., & Medin, D. L. (1981). *Categories and concepts*. Cambridge, MA: Harvard University Press.

Smith, J. D., & Kemier-Nelson, D. G. (1984). Overall similarity in adults' classification: The child in all of us. *Journal of Experimental Psychology: General, 113*, 137–159.

Smith, J. D., & Minda, J. P. (1998). Prototypes in the mist: The early epochs of category learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 24*, 1411–1436.

Smith, J. D., & Minda, J. P. (2000). Thirty categorization results in search of a model. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 26*, 3–27.

Smith, J. D., Minda, J. P., & Washburn, D. A. (2004). Category learning in rhesus monkeys: A study of the Shepard, Hovland, and Jenkins (1961) tasks. *Journal of Experimental Psychology: General, 133*, 398–414.

Smith, J. D., Berg, M. E., Cook, R. G., Murphy, M. S., Crossley, M. J., Boomer, J., … Grace, R. C. (2012). Implicit and explicit categorization: A tale of four species. *Neuroscience & Biobehavioral Reviews*, *36*, 2355–2369.

Smith, L. B. (1989). A model of perceptual classification in children and adults. *Psychological Review, 96*, 125–144.

Smith, L. B., & Heise, D. (1992). Perceptual similarity and conceptual structure. In B. Burnes (Ed.), *Percepts, concepts, and categories: The representation and processing of information* (pp. 233–272). Amsterdam, The Netherlands: Elsevier.

Smith, L. B., & Yu, C. (2008). Infants rapidly learn word-referent mappings via cross-situational statistics. *Cognition, 106*, 1558–1568.

Soja, N. N. (1992). Inferences about the meanings of nouns: The relationship between perception and syntax. *Cognitive Development, 7*, 29–45.

Soja, N. N., Carey, S., & Spelke, E. S. (1991). Ontological categories guide young children's inductions of word meaning: Object terms and substance terms. *Cognition, 38*, 179–211.

Son, J. Y., Smith, L. B., & Goldstone, R. L. (2008). Simplicity and generalization: Short-cutting abstraction in children's object categorizations. *Cognition, 108*, 626–638.

Sowell, E. R., Thompson, P. M., Holmes, C. J., Batth, R., Jernigan, T. L., & Toga, A. W. (1999a). Localizing age-related changes in brain structure between childhood and adolescence using statistical parametric mapping. *NeuroImage, 9*, 587–597.

Sowell, E. R., Thompson, P. M., Holmes, C. J., Jernigan, T. L., & Toga, A. W. (1999b). In vivo evidence for post-adolescent brain maturation in frontal and striatal regions. *Nature Neuroscience, 2*, 859-861.

Spencer, J. P., Blumberg, M. S., McMurray, B., Robinson, S. R., Samuelson, L. K., & Tomblin, J. B. (2009). Short arms and talking eggs: Why we should no longer abide the nativist–empiricist debate. *Child Development Perspectives, 3*, 79–87.

Steyvers, M., & Tenenbaum, J. B. (2005). The large-scale structure of semantic networks: Statistical analyses and a model of semantic growth. *Cognitive Science, 29*, 41–78.

Strauss, M. S. (1979). Abstraction of prototypical information by adults and 10-month-old infants. *Journal of Experimental Psychology: Human Perception and Performance, 5*, 618–632.

Teng, E., Stefanacci, L., Squire, L. R., & Zola, S. M. (2000). Contrasting effects on discrimination learning after hippocampal lesions and conjoint hippocampal-caudate lesions in monkeys. *Journal of Neuroscience, 20*, 3853–3863.

Thapar, A., & McDermott, K. B. (2001). False recall and false recognition induced by presentation of associated words: Effects of retention interval and level of processing. *Memory and Cognition, 29*, 424–432.

Tranel, D., Damasio, H., & Damasio, A. R. (1997). A neural basis for the retrieval of conceptual knowledge. *Neuropsychologia, 35*, 1319–1327.

Tulving, E. (1972). *Organization of memory*. Cambridge, MA: MIT Press.

Tversky, A. (1977). Features of similarity. *Psychological Review, 84*, 327-352.

van Domburg, P. H. M. E, & ten Donkelaar, H. J. (1991). *The human substantia nigra and ventral tegmental area*. Berlin, Germany: Springer-Verlag.

Vogels, R. (1999). Categorization of complex visual images by rhesus monkeys. Part 1: Behavioural study. *European Journal of Neuroscience, 11*, 1223–1238.

Vygotsky, L. S. (1986). *Thought and language*. Cambridge, MA: MIT Press. (Original work published 1934)

Warrington, E. K. (1975). The selective impairment of semantic memory. *Quarterly Journal of Experimental Psychology, 27*, 635–657.

Watanabe, S., Sakamoto, J., & Wakita, M. (1995). Pigeons' discrimination of paintings by Monet and Picasso. *Journal of the Experimental Analysis of Behavior, 63*, 165–174.

Waxman, S. R., & Booth, A. E. (2002). Seeing pink elephants: Fourteen-month-olds' interpretations of novel nouns and adjectives. *Cognitive Psychology, 43*, 217–242.

Waxman, S., & Booth, A. (2003). The origins and evolution of links between word learning and conceptual organization: new evidence from 11-month-olds. *Developmental Science, 6*, 128–135.

Waxman, S. R., & Braun, I. (2005). Consistent (but not variable) names as invitations to form object categories: New evidence from 12-month-old infants. *Cognition, 95*, B59–B68.

Waxman, S. R., & Markow, D. B. (1995). Words as invitations to form categories: Evidence from 12-to 13-month-old infants. *Cognitive Psychology, 29*, 257–302.

Welder, A. N., & Graham, S. A. (2001). The influence of shape similarity and shared labels on infants' inductive inferences about nonobvious object properties. *Child Development, 72*, 1653–1673.

Werker, J. F., Cohen, L. B., Lloyd, V. L., Casasola, M., & Stager, C. L. (1998). Acquisition of word–object associations by 14-month-old infants. *Developmental Psychology, 34*, 1289–1309.

Wills, A. J., & Pothos, E. M. (2012). On the adequacy of current empirical evaluations of formal models of categorization. *Psychological Bulletin, 138*, 102–125.

Wilson, C. (1995). *The contribution of cortical neurons to the firing pattern of striatal spiny neurons*. Cambridge, MA: Bradford.

Winer, G. A. (1980). Class-inclusion reasoning in children: A review of the empirical literature. *Child Development, 51*, 309–328.

Wittgenstein, L. (2010). *Philosophical Investigations*. Hoboken, NJ: Wiley. (Original work published 1953)

Xu, F. (2002). The role of language in acquiring object kind concepts in infancy. *Cognition, 85*, 223–250.

Xu, F., & Tenenbaum, J. B. (2007). Word learning as Bayesian inference. *Psychological Review, 114*, 245.

Yamauchi, T., & Markman, A. B. (1998). Category learning by inference and classification. *Journal of Memory and Language, 39*, 124–148.

Yamauchi, T., & Markman, A. B. (2000). Inference using categories. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *26*, 776–795.

Yim, H., Dennis, S. J., & Sloutsky, V. M. (2013). The development of episodic memory: Items, contexts, and relations. *Psychological Science, 24*, 2163–2172.

Young, M. E., & Wasserman, E. A. (1997). Entropy detection by pigeons: Response to mixed visual displays after same–different discrimination training. *Journal of Experimental Psychology: Animal Behavior Processes, 23*, 157–170.

Young, M. E., & Wasserman, E. A. (2001). Entropy and variability discrimination. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 27*, 278–293.

Younger, B. (1990). Infant categorization: Memory for category-level and specific item information. *Journal of Experimental Child Psychology, 50*, 131–155.

Younger, B. A., & Cohen, L. B. (1985). How infants form categories. *Psychology of Learning and Motivation, 19*, 211–247.

Zelazo, P. D., Müller, U., Frye, D., Marcovitch, S., Argitis, G., Boseovski, J., … Sutherland, A. (2003). The development of executive function in early childhood. *Monographs of the Society for Research in Child Development, 68*(3), vii–137.