

## CHAPTER 1

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# EDUCATING THE EVOLVED MIND

## Conceptual Foundations for an Evolutionary Educational Psychology

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It is widely accepted that all children in modern societies will receive formal and extended instruction in a variety of core domains, such as mathematics, and at the very least they will acquire the basic skills, as in being able to read and write, necessary for employment and day-to-day living in these societies. Unfortunately, the instructional approaches used to achieve these goals and in fact the details of the goals themselves are points of continued and often divisive debate (Hirsch, 1996). At the very least, these debates date to Rousseau's 1762 publication of *Emile*, and are framed by basic assumptions about how children learn and how adults should motivate children to engage in this learning (Rousseau, 1979). At one extreme is a child-centered approach, whereby adults should come to understand how children learn and then construct educational goals and instructional methods around children's learning biases (e.g., McLellan & Dewey, 1895). At the other extreme is the assumption that adults should

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decide the content to be taught in schools, and an accompanying assumption that the methods by which this content is taught should be based on experimental studies of learning, often without much consideration of children's preferences (e.g., Thorndike, 1922). In addition to this lack of consensus about how to approach children's learning, educational goals can be further complicated by attempts to use schools to socialize children in one ideological perspective or another (MacDonald, 1988).

One example of the latter concerns attempts to include the teaching of "intelligent design" along with natural selection in biology courses in some regions of the United States; the former is the argument that the complexity of life implicates a designer and by inference a "God." Research in biology strongly supports the teaching of natural selection, but these mechanisms are at odds with certain religious beliefs, which in turn are the ideological basis for attempts to modify the school curriculum. The use of schools to shape the ideological biases of the next generation is by no means restricted to the United States, and is ironically understandable from an evolutionary perspective (see MacDonald, 1988). The details are not important for the current discussion: My point is that schools present an opportunity for large-scale socialization of children and are thus often used for purposes that have more to do with the best interests of those attempting to influence this socialization than the best educational interests of children. In fact, the history of education in the United States might be viewed as being more strongly driven by ideology and untested assumptions about children's learning than by concerns about the efficacy of schooling vis-à-vis the long-term social and employment interests of children (Ceci & Piaperino, 2005; Egan, 2002; Hirsch, 1996).

These ideological debates and the attendant opportunity costs to children's educational outcomes and later employment opportunities will continue well into the twenty-first century, if current attempts to move the field of education to a more solid scientific footing are not successful (Reyna, 2005). With this monograph, I hope to provide a broad and scientifically grounded perspective on these debates by considering how children's schooling and to a lesser degree their later occupational interests can be informed by recent advances in the application of evolutionary theory to the understanding of the human brain, mind, and its development (Bjorklund & Pellegrini, 2002; Cosmides & Tooby, 1994; Geary, 2005; Hirschfeld & Gelman, 1994; Pinker, 1997). I have termed this perspective *evolutionary educational psychology* (Geary, 2002a), but I must emphasize at the outset that this is not a perspective that is ready for direct translation into school curricula. Rather, I will outline the foundations for this discipline, and in doing so I hope to (a) provide a conceptualization of children's learning in school that is less prone to ideological change; (b) consider ways in which this perspective can be used to generate testable empirical hypotheses

about this learning; and (c) discuss implications for understanding and ultimately improving educational outcomes.

In the first section, I make a distinction between *biologically primary* folk knowledge and abilities, that is, competencies that are components of evolved cognitive domains, and *biologically secondary* knowledge and abilities, that is, competencies acquired through formal or informal training. In this first section, I focus on primary abilities because these are the foundation for the construction of secondary abilities through formal education. In the second section, I discuss the evolution of general intelligence and how this evolution relates to the primary abilities discussed in the first section. In these first two sections, I provide more detail than might, at first read, seem to be needed. The details are necessary, however, if we are going to make a serious attempt to understand academic learning from an evolutionary perspective and are going to generate explicit and testable hypotheses about the relation between evolved cognitive and social biases and this learning. In the final section, I discuss the historical and schooling-based emergence of secondary abilities, focusing on potential cognitive and social mechanisms involved in the building of secondary competencies, and using reading and scientific reasoning as examples.

## COGNITIVE EVOLUTION AND CHILDREN'S DEVELOPMENT

To fully appreciate the enormity of the task of educating millions of children, it is helpful to contrast the abilities and forms of knowledge the human brain is biologically primed to learn and those abilities and forms of knowledge without this advantage but that are needed for successful living in the modern world. The former are termed biologically primary and the culture-specific skills that can be built from these are termed biologically secondary (Geary, 1995). At this point, the distinction between these categories is necessarily fuzzy, but such a distinction is an important first step to approaching children's academic development from an evolutionarily informed perspective. First, I will outline broad distinctions between primary and secondary domains. Next, I describe a taxonomy of primary domains for the human mind, and finally I discuss how children's cognitive development and self-directed activity biases are related to these primary domains.

### Primary and Secondary Forms of Cognition

Biologically primary *domains* encompass evolutionary-significant content areas (described below) and are composed of *folk knowledge* (e.g., inferential biases) and *primary abilities* (e.g., language, spatial). Folk knowl-

edge results from the organization of the brain systems that have evolved to process and integrate specific forms of information. These brain regions and associated perceptual and attentional biases focus the individual on these features of the environment and prime the forms of behavioral response that tended to covary with survival or reproductive outcomes during the species' evolutionary history. For many species, there is evidence for specialized systems for detecting features of conspecifics (i.e., members of the same species; Grossman et al., 2000; Kanwisher, McDermott, & Chun, 1997), and different systems for detecting features of typical prey (Barton & Dean, 1993) or predatory (Deecke, Slater, & Ford, 2002) species. These brain, perceptual, and attentional systems are likely to be modularized, that is, they respond to restricted forms of information (e.g., movement of a predator) and prime a restricted class of behavioral response (e.g., predator evasion), but this does not mean the systems cannot be modified based on experience. The extent of any such plasticity is vigorously debated (Clark, Mitra, & Wang, 2001; de Winter & Oxnard, 2001; Finlay, Darlington, & Nicastro, 2001) and, as I describe later, likely varies across modules and development (Geary, 2005; Geary & Huffman, 2002).

In any case, because these perceptual and attentional biases result from the organization of the underlying sensory and brain systems, folk knowledge is largely implicit, that is, the systems operate more or less automatically and below conscious awareness. For these examples, animals of many species behave in ways consistent with an "intuitive" understanding or folk knowledge of how to engage in social interactions with members of their own species and how to hunt and avoid predators (see Gigerenzer, Todd, & ABC Research Group, 1999).

For humans, folk knowledge can sometimes be expressed explicitly and in terms of attributional biases about the behavior of other people (Fiske & Taylor, 1991) or about physical (Clement, 1982) or biological (Atran, 1998) phenomena. Folk knowledge is organized around a constellation of more specialized primary abilities. As an example, the domain of folk psychology includes implicit and sometimes explicit knowledge organized around the self, specific other individuals (e.g., family members), and group-level dynamics, and these knowledge bases are composed of more specific primary abilities. For individual-level folk knowledge, these specific abilities emerge from the brain, perceptual, and cognitive systems that support language, facial processing, gesture processing, and so forth, as described below. The constellation of brain regions that support each of these and related abilities may differ (e.g., Belin, Zatorre, Lafaille, Ahad, & Pike, 2000; Downing, Jiang, Shuman, & Kanwisher, 2001; Kanwisher et al., 1997), but during social discourse they operate in a coordinated manner. The distinction between specific primary abilities is

important, because different primary abilities may differentially contribute to the construction of different secondary abilities, as discussed later under the heading Biologically Secondary Learning.

Academic learning involves the modification of primary abilities and explicit attributional biases associated with folk knowledge to create a suite of culture-specific biologically secondary domains, such as mathematics, and biologically secondary abilities and knowledge, such as the ability to phonetically decode written symbols or to understand the base-10 structure of the formal mathematical number system (Geary, 1995, 2002a, 2006). Of course, some secondary abilities are more similar to primary abilities than are others. Spelke (2000), for instance, proposed that learning the mathematical number system involves integrating implicit and primary knowledge of small numbers (e.g., implicitly representing the quantity of small,  $\leq 4$ , sets) and counting principles with another primary ability that enables an analog representation of magnitude, as in the ability to implicitly estimate more than or less than (Pinel, Piazza, Le Bihan, & Dehaene, 2004). Primary knowledge of the numerosity of small collections of objects and the understanding that successive counts increase quantity by one is integrated with the magnitude representation system through a culture-specific system of number words, such that number words come to represent specific quantities outside the range of the primary system. The end result is the ability to represent large quantities verbally or in terms of a formal mathematical number line, that is, to abstractly represent large quantities in a precise manner and in a way that is unique in terms of our evolutionary history. Siegler and Opfer's (2003) research on children's number-line estimation is consistent with this proposal; specifically, when estimating where an Arabic numeral should be placed on a number line, first grade children's estimates conform to predictions of the primary analog magnitude system, but with schooling these estimates eventually conform to the formal secondary mathematical system.

Other features of academic mathematics, such as the base-10 system, are more remote from the supporting primary abilities (Geary, 2002a). Competency in base-10 arithmetic requires a conceptual understanding of the mathematical number line, and an ability to decompose this system into sets of 10 and then to organize these sets into clusters of 100 (i.e., 10, 20, 30, ...), 1,000, and so forth. Whereas an implicit understanding of the quantity of small sets of objects is likely to be primary knowledge, the creation of sets around 10 and the superordinate organization of these sets is clearly not. This conceptual knowledge must also be systematically mapped onto the number word system (McCloskey, Sokol, & Goodman, 1986), and integrated with school-taught procedures for solving complex arithmetic problems (Fuson & Kwon, 1992; Geary, 1994). The develop-

ment of base-10 knowledge thus requires the extension of primary number knowledge to very large numbers; the organization of these number representations in ways that differ conceptually from primary knowledge; and, the learning of procedural rules for applying this new knowledge to the secondary domain of complex, mathematical arithmetic (e.g., to solve  $234 + 697$ ).

### **Evolved Domains of the Human Mind**

I assume that primary knowledge and abilities provide the foundation for academic learning. Thus, crucial components for an evolutionary approach to education include knowledge of the organization of primary domains; the extent to which the associated abilities are plastic; and the form and range of species-typical experiences that transform this plasticity into systems well suited to the particulars of the ecology and social group within which children are situated. Unfortunately, we do not yet have all of the pieces of this foundational knowledge, but enough is now known to provide the framework for an evolutionary educational psychology. In the following sections, I provide the cornerstones of this foundation; that is, I: (a) outline a motivation-to-control model that provides a conceptual organization to many levels of evolved traits; (b) describe a taxonomy of primary domains and abilities in humans; and (c) consider the relation between evolution and cognitive development.

#### ***Motivation to Control***

The brain and mind of all species evolved to attend to and process the forms of information, such as the movement patterns of prey species, which covaried with survival and reproductive prospects during the species' evolutionary history (Geary, 2005). These systems bias implicit decision-making processes and behavioral responses in ways that allow the organism to attempt to achieve access to and control of these outcomes, as in prey capture, or to avoid negative outcomes, as in being captured by a predator (see Gigerenzer et al., 1999). The framework fits well with the general consensus among psychologists that humans have a basic motivation to achieve some level of control over relationships, events, and resources that are of significance in their life (Fiske, 1993; Heckhausen & Schulz, 1995; Shapiro, Schwartz, & Astin, 1996; Thompson, Armstrong, & Thomas, 1998), although there is no consensus as to whether this motivation to control is the result of evolution. My thesis is that the human motivation to control is indeed an evolved disposition, but should not be confused with an explicit goal to control others. Rather, it is a conceptual heuristic for understanding the foci of behavior; that is, the implicit focus

of behavior is to attempt to influence social relationships and the behavior of other people in self-serving ways (often masked by self deception; Trivers, 2000), and to gain control of the biological and physical resources that enhance social status and well-being in the local ecology and social group (Geary, 1998, 2005).

The control-related behavioral focus is represented by the apex and adjoining section of Figure 1.1. The bottom of the figure represents the folk modules that in effect result in a bottom-up directing of the individual's attention toward and enable the automatic and implicit processing of social (e.g., facial expressions), biological (e.g., features of hunted species), and physical (e.g., manipulation of objects as tools) information patterns that have tended to be the same across generations and within lifetimes, and have covaried with survival or reproductive prospects during human evolution. The center of the figure represents conscious psychological and cognitive (e.g., working memory) mechanisms that enable more top-down strategic planning and problem solving and that provide affective feedback regarding the effectiveness of actual or mentally simulated control-related behaviors, as described below.

***Benefits of Control.*** If there is indeed an evolved motivation to control, then there should be a relation between achievement of resource control and social influence and survival and reproductive outcomes. In modern societies, some resources are symbolic (e.g., money, stocks) but are important because control of these resources enhances social influence and facilitates control of quality foods, medicines, housing, and so forth. In traditional societies, coalitions of kin cooperate to control local biological (e.g., cows) and physical (e.g., grazing land) resources, and to compete with other coalitions to maintain control of these resources. Although humans have psychological mechanisms that obscure the fact that they often use social relationships and other people for their own ends (Alexander, 1989), use them they do. Other people are resources if they have reproductive potential (e.g., young females; Buss, 1994), social power, or access (e.g., through monetary wealth) to the biological and physical resources that covary with well-being and status in the culture (Irons, 1979). The goal of developing a relationship with an individual who has social power and wealth is fundamentally an attempt to influence the behavior of this individual and through this to achieve access to power and wealth (Fiske, 1993; Geary & Flinn, 2001). In most contexts and for most people, the motivation to control is constrained by formal laws, informal social mores (e.g., enforced through gossip; Barkow, 1992), and by psychological mechanisms (e.g., guilt) that promote social compromise and reciprocal social relationships with members of their in-group (Baron, 1997; Trivers, 1971).

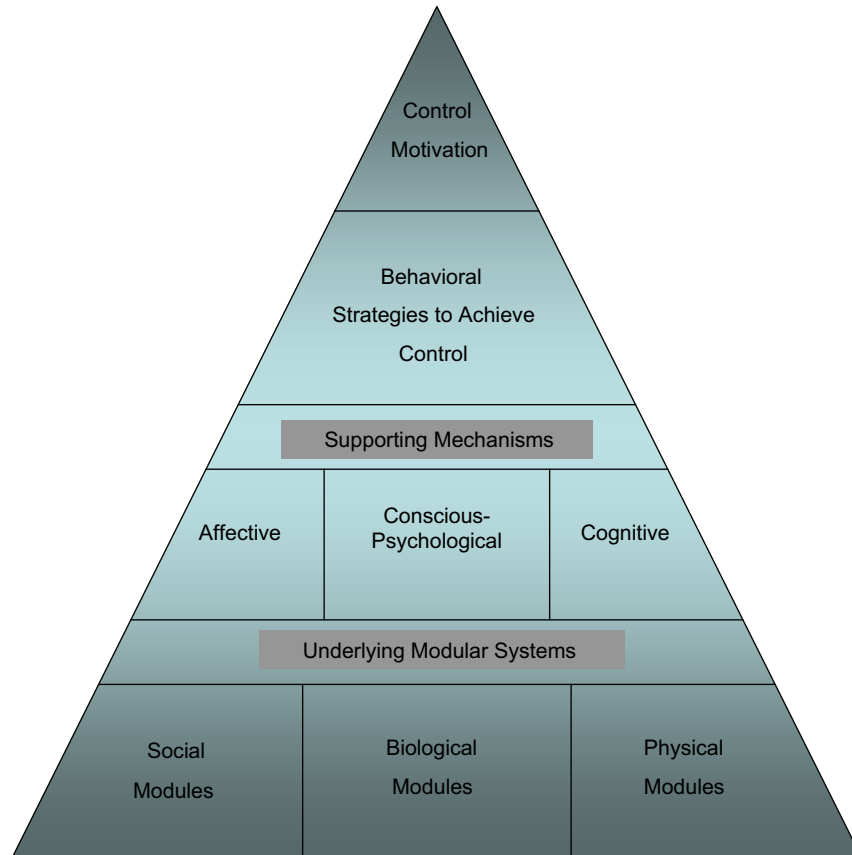


Figure 1.1. The apex and following section represent the proposal that human behavior is basically driven by a motivation to control the social, biological, and physical resources that have tended to covary survival and reproductive outcomes during human evolution. The midsection shows the supporting affective, conscious psychological (e.g., attributional biases), and cognitive (e.g., working memory) mechanisms that support the motivation to control and operate on the modular systems shown at the base. From *"The origin of mind: Evolution of brain, cognition, and general intelligence,"* by D. C. Geary, p. 74. Copyright 2005 by the American Psychological Association. Reprinted with permission.

Nonetheless, even in resource-rich Western culture, socioeconomic status (SES), that is, control of symbolic (e.g., money) and material resources, is associated with a longer life span and better physical health (e.g., Adler et al., 1994; R. Bradley & Corwyn, 2002), although it is not correlated with happiness or the subjective evaluation of well-being (Diener &



Diener, 1996). The ability to achieve high SES in modern societies is related, in part, to general intelligence (described below) which in turn may moderate the relation between SES and health outcomes (e.g., through better compliance to medical regimes; L. S. Gottfredson, 2004); or, general intelligence may covary directly with overall health (Lubinski & Humphreys, 1992). In any case, in preindustrial and industrializing Western societies, and in traditional societies today (Hill & Hurtado, 1996; United Nations, 1985), SES was considerably more important than it currently is in Western culture (e.g., Hed, 1987; Morrison, Kirshner, & Molho, 1977; Schultz, 1991). In fact, parental SES often influenced which infants and young children would live and which would die. During the 1437-1438 and 1449-1450 epidemics in Florence, Italy, child mortality rates increased 5- to 10-fold and varied with parental SES; higher parental SES was associated with lower mortality (Morrison et al., 1977). In an extensive analysis of birth, death, and demographic records from eighteenth century Berlin, Schultz (1991) found a strong negative correlation ( $r = -.74$ ) between parental SES and infant and child mortality rates. Infant (birth to 1 year) mortality rates were about 10% for aristocrats but more than 40% for laborers and unskilled technicians.

Given these relations, it is not surprising that individual and group-level conflicts of interest are invariably over access to and control of social relationships, the behavior of other people, and the biological and physical resources that covary with survival or reproductive prospects in the local ecology and culture (Alexander, 1979; Chagnon, 1988; Horowitz, 2001; Irons, 1979; Keeley, 1996). Although these relations are often masked by the wealth and low mortality rates enjoyed in Western societies today, the implication is clear: In most human societies and presumably throughout human evolution, gaining social influence and control of biological and physical resources, that is, food, medicine, shelter, land, and so forth, covaried with reproductive opportunity (i.e., choice of mating partner), reproductive success (i.e., the number of offspring surviving to adulthood), and survival prospects. Recent population genetic studies provide strong support for the hypothesis that resource control enhances reproductive prospects (e.g., Zerjal et al., 2003).

A fundamental motivation to control has evolved in humans, because success at achieving control of social, biological, and physical resources very often meant the difference between living and dying. My point is that evolved motivational systems bias children such that they prefer to engage in activities, such as forming social relationships (e.g., Geary, Byrd-Craven, Hoard, Vigil, & Numtee, 2003), that flesh out the primary abilities and knowledge that were the foci of competition for behavioral control and social influence during human evolution, but these activities are often very different from the activities needed to master a biologically

secondary academic domain. The contrast between evolved motivational biases and the activities needed for secondary learning has very important implications for children's motivation to learn in school and niche seeking in other evolutionarily novel contexts, such as the work place, as I elaborate in the section Motivation to Learn.

***Conscious Psychological Mechanisms.*** The core psychological mechanism presented in Figure 1.1 is the ability to generate conscious, explicit mental representations of situations that are centered on the self and one's relationship with other people or one's access to biological and physical resources that are of significance in the culture and ecology. The representations are of past, present, or potential future states and might be cast as visual images, in language, or as memories of personal experiences, that is, episodic memories (Tulving, 2002). Of central importance is the ability to create a mental representation of a desired or fantasized state, such as a relationship with another individual, and to compare this to a mental representation of one's current state, such as the nature of the current relationship with this other individual. These are conscious psychological representations of present and potential future states that are of personal significance and are the content on which more explicit and effortful everyday reasoning and problem-solving processes, such as analogy and induction, are applied (Evans, 2002; Holyoak & Thagard, 1997; Stanovich & West, 2000). The goal is to devise and rehearse behavioral strategies that can be used to reduce the difference between the current and desired state (Geary, 2005). Explicit attributions about the self, other people, groups, as well as the behavior of other species or physical phenomena, are also components of these conscious psychological representations, as I describe in the section titled Heuristics and Attributional Biases.

***Cognitive Mechanisms.*** The cognitive mechanisms include working memory, attentional control, and the ability to inhibit automatic processing of folk-related information (e.g., attributional biases) or to inhibit evolved behavioral reactions to this information (Baddeley, 1986; 2000a; Bjorklund & Harnishfeger, 1995; Cowan, 1995), as well as the ability to systematically problem solve and reason about patterns represented in working memory (Newell & Simon, 1972). These cognitive and problem-solving processes are the mechanisms that allow individuals to mentally represent and manipulate information processed by perceptual systems (e.g., sounds and words) and the more complex forms of information that result from the integration of information processed by the social, biological, and physical modules. Working memory, for instance, enables the short-term retention of spoken utterances, which may facilitate vocabulary learning and other specific primary abilities (Baddeley, Gathercole, & Papagno, 1998).

However, my proposal is that the most important evolutionary function concerns the relation between these cognitive and problem-solving mechanisms and the generation and manipulation of conscious psychological representations (Geary, 2005). In other words, working memory and attentional and inhibitory control are the content-free mechanisms that, for instance, enable the integration of a current conscious psychological state with memory representations of related past experiences, and the generation of mental models or simulations of potential future states (Alexander, 1989; Johnson-Laird, 1983). Everyday reasoning and problem solving represent the ways in which these simulations are manipulated in the associated problem space, as individuals generate representations of behavioral or social strategies that will move them from the current state to the desired goal (Newell & Simon, 1972).

***Evolutionary Function.*** The predicted evolved function of these cognitive and conscious psychological mechanisms is to generate a fantasy representation of how the world “should” operate, that is, a representation of the world that would be most favorable to the individual’s reproductive (e.g., fantasy of the “perfect” mate—Whissell, 1996) and survival interests (Geary, 1998, 2005). This mental representation serves as a goal to be achieved and is compared against a mental representation of current circumstances. Working memory serves as the platform, and problem solving (e.g., means-ends analysis; Newell & Simon, 1972) and everyday reasoning processes serve as the means for simulating social and other behavioral strategies that will reduce the difference between the ideal and actual states. If the behavioral strategies are effective, then the difference between the ideal state and the current state will be reduced and the individual will be one step closer to gaining access to and control of social and other resources.

Following Damasio’s (2003) distinction, affective mechanisms are separated into emotions, which are observable behaviors (e.g., facial expressions or social withdrawal), and feelings, which are nonobservable conscious representations of an emotional state or other conditions that can potentially influence the individuals’ well being. Affective mechanisms can influence behavioral strategies. Emotions provide social feedback (e.g., a frown may automatically signal disapproval) and the associated feelings provide feedback to the individual (Campos, Campos, & Barrett, 1989). The latter provides an indicator of the effectiveness of control-related behavioral strategies. Positive feelings provide reinforcement when strategies are resulting in the achievement of significant goals, or at least a reduction in the difference between the current and desired state, and punishment (negative feelings) and disengagement when behaviors are not resulting in this end (J. A. Gray, 1987).

The supporting brain systems should function, in part, to amplify attention to evolutionarily significant forms of information, such as facial expressions, and produce emotions and feelings and prime corresponding behavioral biases that are likely to reproduce outcomes that have covaried with successful survival or reproduction during human evolution (Damasio, 2003; Lazarus, 1991; Öhman, 2002). For instance, positive affect should function, in part, to maintain the forms of social relationship that are commonly associated with the achievement of survival and reproductive ends, and this appears to be the case. Happiness is strongly related to the strength of reciprocal and romantic relationships (Diener & Seligman, 2002), the former being sources of social support and allies during times of social conflict and the latter obviously related to reproductive goals.

### **Taxonomy of Biologically Primary Domains**

The taxonomy of biologically primary folk domains and abilities shown in Figure 1.2 fleshes out the base of Figure 1.1 (Geary, 2005). At this time, there is vigorous debate regarding the broader question of whether these types of cognitive systems are better conceptualized as inherently modular in organization (Cosmides & Tooby, 1994; Gallistel, 2000; Pinker, 1997; Pinker & Jackendoff, 2005) or as generally plastic, with any modular-like competencies emerging through an interaction between relatively unspecialized brain and perceptual systems and patterns of experience (Elman, Bates, Johnson, Karmiloff-Smith, Parisi, & Plunkett, 1996; Hauser, Chomsky, & Fitch, 2002; Heyes, 2003; Quartz & Sejnowski, 1997). The full implications of and resolutions to these debates will likely be decades in coming, but there are a few points relevant to the current discussion.

First, the cognitive abilities (e.g., reading of facial expressions) associated with the folk domains (e.g., folk psychology) illustrated in Figure 1.2 can be conceptualized as modular in that attentional and information-processing biases and information organization in long-term memory appear to be organized in ways consistent with this taxonomy. However, this organization can be built from multiple lower-level systems, and thus a simple one-to-one correspondence between these cognitive abilities and a specific brain region is not always expected. Although brain regions that differentially respond to evolutionarily significant forms of information, such as the shape of a human face or body, are predicted (Kanwisher et al., 1997; Slaughter, Stone, & Reed, 2004), these regions may also respond to perceptually similar forms of information. Moreover, many primary abilities will involve the coordinated activity of multiple lower-

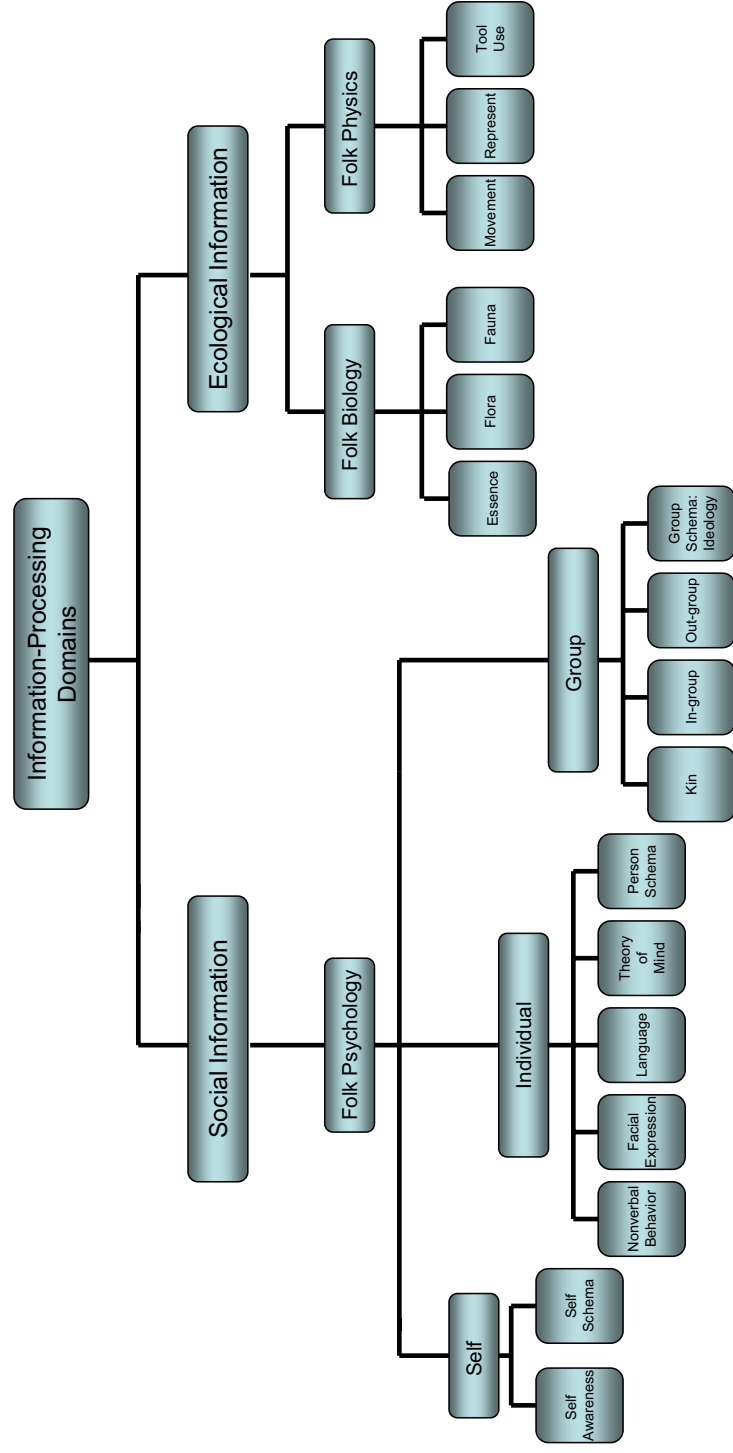


Figure 1.2. Evolved cognitive modules that compose the domains of folk psychology, folk biology, and folk physics. From “*The origin of mind: Evolution of brain, cognition, and general intelligence*,” by D. C. Geary, p. 129. Copyright 2005 by the American Psychological Association. Reprinted with permission.

level perceptual systems and thus result in the distribution of activity across multiple brain regions. As I describe in the section titled Cognitive Development and Modular Plasticity, these modular systems are neither strictly inherently modular nor strictly the result of patterns of developmental experience, but rather are predicted to emerge epigenetically from an interaction between inherent perceptual and attentional biases and evolutionarily expectant developmental experiences (Bjorklund & Pellegrini, 2002; Geary & Bjorklund, 2000; Greenough, Black, & Wallace, 1987; Scarr, 1992, 1993). The relative importance of inherent constraints and patterns of developmental experience is predicted to vary from one module to the next (see below), and thus broad generalizations about the contributions of evolution versus development are not appropriate.

Second, I am in agreement with Marcus' (2004) proposal that brain systems that process restricted forms of information, such as angular orientation or object location, might be considered modular at a neural level and serve as building blocks for multiple higher-level perceptual modules, such as perceiving different specific objects. Each perceptual module can be used as a building block for multiple higher-level modules (e.g., a specific object categorized as a tool). In other words, lower-level modular systems can be used as building blocks for multiple higher-level modules, meaning that complex modular skills (e.g., tool use) emerge developmentally and evolutionarily through a template that organizes preexisting lower-level modules but can do so in novel, environmentally contingent ways. From this perspective, a complex cognitive module does not have to evolve *de novo*, but rather can emerge with an evolutionary duplication or modification of an existing template. The template organizes lower-level systems in a novel way, with no need for evolutionary change in the lower-level systems (Geary, 2005). Marcus' (2004) building blocks imply that basic sensory and perceptual systems have evolved such that they can be configured in many different ways, making them subject to evolutionary and developmental change. The latter contributes to the potential for the "construction" of biologically secondary abilities, within constraints.

### ***Folk Psychology***

Folk psychology is composed of the affective, cognitive, and behavioral systems that enable people to negotiate social interactions and relationships. The function of the corresponding primary cognitive abilities is to process and manipulate (e.g., create categories) the forms of social information that have covaried with survival and reproduction during human evolution. The associated domains involve the self, relationships and interactions with other people, and group-level relationships and interactions. These dynamics are supported by the respective primary modular

systems corresponding to self, individual, and group shown in the bottom and leftmost sections of Figure 1.2.

**Self.** Although there is much that remains to be resolved regarding the nature and distinctiveness of self-related cognitions versus those related to other people and the distribution of these representations in the brain (Gillihan & Farah, 2005), people in general often have a self-referenced perspective on social relationships and other matters of significance in their life (Fiske & Taylor, 1991). Self-related cognitions include awareness of the self as a social being and of one's behavior in social contexts (Tulving, 2002), as well as a self schema (Markus, 1977). The self schema is a long-term memory network of information that links together knowledge and beliefs about the self, including positive (accentuated) and negative (discounted) traits (e.g., friendliness), personal memories, self-efficacy in various domains, and so on. Whether implicitly or explicitly represented, self schemas appear to regulate goal-related behaviors—specifically, where one focuses behavioral effort and whether or not one will persist in the face of failure (Sheeran & Orbell, 2000). Self-related regulation results from a combination of implicit and explicit processes that influence social comparisons, self-esteem, valuation of different forms of ability and interests, and the formation of social relationships (Drigotas, 2002).

**Individual.** The person-related modular competencies function to enable the monitoring and control of dyadic interactions and the development and maintenance of one-on-one relationships. Caporael (1997) and Bugental (2000) have described universal forms of these interactions and relationships, including parent-child attachments and friendships, among others. There are, of course, differences across these dyads, but all of them are supported by the individual-level modules shown in Figure 1.2. These modules include those that enable the reading of nonverbal behavior and facial expressions, language, and theory of mind (e.g., Baron-Cohen, 1995; Brothers & Ring, 1992; Pinker, 1994; Rosenthal, Hall, DiMatteo, Rogers, & Archer, 1979). Theory of mind refers to the ability to make inferences about other people, including their beliefs and motives underlying their behavior, their future intentions, and so forth. The person schema is a long-term memory network that includes representations of other people's physical attributes (age, race, sex), memories for specific behavioral episodes, and more abstract trait information, such as people's sociability (e.g., warm to emotionally distant) and competence (Schneider, 1973). It seems likely that the person schema will also include information related to other people's modular systems, such as theory of mind, as well as people's network of social relationships and kin (Geary & Flinn, 2001). The former would include memories and trait information

about how the person typically makes inferences, responds to social cues, and their social and other goals.

**Group.** A universal aspect of human behavior and cognition is the parsing of the social world into groups (Fiske, 2002). The most common of these groupings are shown in Figure 1.2, and reflect the categorical significance of kin, the formation of in-groups and out-groups, and a group schema. The latter is an ideologically-based social identification, as exemplified by nationality or religious affiliation. The categorical significance of kin is most strongly reflected in the motivational disposition of humans to organize themselves into families of one form or another in all cultures (Brown, 1991). In traditional societies, nuclear families are typically embedded in the context of a wider network of kin (Geary & Flinn, 2001). Individuals within these kinship networks cooperate to facilitate competition with other kin groups over resource control and manipulation of reproductive relationships. As cogently argued by Alexander (1979), coalitional competition also occurs beyond the kin group, is related to social ideology, and is endemic throughout the world (Horowitz, 2001). As with kin groups, competition among ideology-based groups is over resource control. The corresponding selective pressure is the competitive advantage associated with large group size; that is, ideologies enable easy expansion of group size during group-level competition (Alexander, 1989).

### ***Folk Biology and Folk Physics***

People living in traditional societies use the local ecology to support their survival and reproductive needs. The associated activities are supported by, among other things, the folk biological and folk physical modules shown in the ecological section of Figure 1.2 (Geary, 2005; Geary & Huffman, 2002). The folk biological modules support the categorizing of flora and fauna in the local ecology, especially species used as food, medicines, or in social rituals (Berlin, Breedlove, & Raven, 1973). Folk biology also includes systems that support an understanding of the essence of these species (Atran, 1998), that is, heuristic-based decisions regarding the likely behavior of these species in contexts relevant to human interests. Essence also includes explicit knowledge about growth patterns and behavior that facilitates hunting and other activities involved in securing and using these species as resources (e.g., food). Physical modules are for guiding movement in three-dimensional physical space, mentally representing this space (e.g., demarcating the in-group's territory), and for using physical materials (e.g., stones, metals) for making tools (Pinker, 1997; Shepard, 1994). The associated primary abilities support a host of evolutionarily significant activities, such as hunting, foraging, and the use of tools as weapons. Finally, there may also be evolved systems for repre-



senting small quantities, as noted earlier, and for manipulating these representations by means of counting and simple additions and subtractions (Geary, 1995). On the basis of correlated brain regions (e.g., Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999), these primary quantitative abilities may be aspects of folk physics.

### ***Heuristics and Attributional Biases***

In addition to describing “rule of thumb” patterns of behavior (Gigerenzer et al., 1999), heuristics can also include explicit inferential and attributional biases that are integral features of folk knowledge, at least for humans. For instance, people often make attributions about the cause of failures to achieve social influence or other desired outcomes, including academic achievement goals. An attribution of this type might involve an explicit evaluation about the reason for one’s failure to achieve a desired outcome—determining, for example, that the failure was due to bad luck—and would function to direct and maintain control-related behavioral strategies in the face of any such failure (Heckhausen & Schultz, 1995). Social attributional biases that favor members of the in-group and derogate members of out-groups are also well known (Fiske, 2002; W. Stephan, 1985) and facilitate coalitional competition (Horowitz, 2001). The essence associated with folk biology allows people to make inferences (e.g., during the act of hunting) about the behavior of members of familiar species, as well as about the likely behavior of less familiar but related species (Atran, 1998). Attributions about causality in the physical world have also been studied. Children and adults have, as an example, naïve conceptions about motion and other physical phenomena (Clement, 1982).

These biases may often provide good enough explanations for day-to-day living and self-serving explanations for social and other phenomena, but this does not mean all of the explanations are accurate from a scientific perspective. Explicit descriptions of these psychological, physical, and biological phenomena are often times correct, especially for basic relationships (Wellman & Gelman, 1992), but many of these explanations and attributional biases are scientifically inaccurate and may actually interfere with the learning of scientific concepts, as I illustrate in the section titled Academic Learning.

### **Cognitive Development and Modular Plasticity**

With an evolutionary perspective on education, it is important to distinguish cognitive development and academic development (Geary, 1995, 2004). The former is concerned with the evolved function of developmen-

tal activities as related to the adaptation of primary abilities to local conditions. Empirically, it is known that for many of the folk abilities (e.g., language) represented by Figure 1.2, plasticity appears to be especially evident during the early developmental period (Kuhl, 1994; Kuhl et al., 1997; Pascalis, de Haan, & Nelson, 2002; Pascalis, Scott, Shannon, Nicholson, Coleman, & Nelson, 2005; Paterson, Brown, Gsödl, Johnson, & Karmiloff-Smith, 1999; Stiles, 2000). Given the potential cost of death before reproductive maturity, the benefits associated with a long developmental period and the presumed corresponding increase in brain and cognitive plasticity must be substantial. In fact, evidence in the fossil record suggests that the human developmental period nearly doubled with the emergence of modern humans (Dean et al., 2001), with particular increases in the length of childhood and adolescence (Bogin, 1999). The extension of the length of the developmental period appears to have coevolved with changes in brain size and organization, among other changes (Flinn, Geary, Ward, 2005; Geary, 2005). One implication is that the increase in the period of immaturity and the attendant increase in the period of brain and cognitive plasticity serves to accommodate greater variation in the conditions in which evolving humans were situated, as I elaborate in the section titled *Evolution of General Intelligence*.

The mechanisms involved in the experience-driven adaptation of primary modular systems to variation in local conditions are not well understood. At a macro level, and following the lead of R. Gelman (1990), Geary and Huffman (2002) proposed that prenatal brain organization results in inherently constrained features of neural and perceptual modules that guide attention to and processing of stable forms of information (e.g., the general shape of the human face) in the folk domains shown in Figure 1.2. The result is biases in early postnatal attentional, affective, and information-processing capacities, as well as biases in self-initiated behavioral engagement of the environment (Bjorklund & Pellegrini, 2002; Scarr, 1992; Scarr & McCartney, 1983). The latter generate evolutionarily expectant experiences, that is, experiences that provide the social and ecological feedback needed to adjust modular architecture to variation in information patterns in these domains (Bouchard, Lykken, Tellegen, & McGue, 1996; Greenough et al., 1987; MacDonald, 1992). These behavioral biases are expressed as common juvenile activities, such as social play and exploration of the ecology. These experience-expectant processes result in the modification of plastic features of primary modular systems, such that the individual is able to identify and respond to variation (e.g., discriminate one individual from another) within these folk domains, and begin to create the forms of category described above, such as in-groups/out-groups or flora/fauna.

### ***Folk Psychology***

As an illustration of the importance of plasticity in a folk domain, consider that the strong bias of human infants to attend to human faces, movement patterns, and speech reflects, in theory, the initial and inherent organizational and motivational structure of the associated folk psychological modules (Freedman, 1974). These biases reflect the evolutionary significance of social relationships (Baumeister & Leary, 1995) and in effect recreate the microconditions (e.g., parent-child interactions) associated with the evolution of the corresponding modules (Caporael, 1997). Attention to and processing of this information also provides exposure to the within-category variation needed to adapt the architecture of these modules to variation in parental faces, behavior, and so forth (R. Gelman & Williams, 1998; Pascalis et al., 2005). It allows the infant to discriminate a parent's voice or face from that of other potential parents with only minimal exposure. Indeed, when human fetuses (gestation age of about 38 weeks) are exposed in utero to human voices, their heart-rate patterns suggest they are sensitive to and learn the voice patterns of their mother, and discriminate her voice from that of other women (Kisilevsky et al., 2003).

Developmental experiences may also facilitate later category formation. Boys' group-level competition (e.g., team sports) provides one example of the early formation of competition based on in-groups and out-groups and the coordination of social activities that may provide the practice for primitive group-level warfare in adulthood (Geary, 1998; Geary et al., 2003). These natural games may provide the practice needed for the skilled formation and maintenance of social coalitions in adulthood, and result in the accumulation of memories for associated activities and social strategies. In other words and in keeping with the comparative analyses of Pellis and Iwaniuk (2000), these games may be more strongly related to learning the skills of other boys and acquiring the social competencies for coordinated group-level activities, as contrasted with learning specific fighting behaviors, such as hitting. These activities and the accompanying effects on brain and cognition are in theory related to the group-level social selection pressures noted earlier, and provide experience with the dynamic formation of in-groups and out-groups.

### ***Folk Biology and Folk Physics***

The complexity of hunting and foraging activities varies with the ecology in which the group lives, a situation that should select for plasticity in the associated brain, cognitive, and behavioral systems (S. Gelman, 2003). In theory, children's implicit folk biological knowledge and inherent interest in living things result in the motivation to engage in experiences that automatically create implicit taxonomies of local flora and fauna and

result in the accrual of an extensive knowledge base of these species (Wellman & Gelman, 1992). In traditional societies, these experiences include assisting with foraging and play hunting (e.g., Blurton Jones, Hawkes, & O'Connell, 1997). Anthropological research indicates that it often takes many years of engaging in these forms of play and early work to learn the skills (e.g., how to shoot a bow and arrow) and acquire the knowledge needed for successful hunting and foraging (Kaplan, Hill, Lancaster, & Hurtado, 2000), although this is not the case with all hunting and foraging activities (Blurton Jones & Marlowe, 2002).

An example associated with folk physics is provided by the ability to mentally form maplike representations of the large-scale environment, which occurs more or less automatically as animals explore this environment (Gallistel, 1990; Wellman & Gelman, 1992). For humans, the initial ability to form these representations emerges by three years of age (DeLoache, Kolstad, & Anderson, 1991), improves gradually through adolescence, and often requires extensive exploration and exposure to the local environment to perfect (Matthews, 1992). The research of Matthews clearly shows that children automatically attend to geometric features of the large-scale environment and landmarks within this environment and are able to generate a cognitive representation of landmarks and their geometric relations at a later time. Children's skill at generating these representations increases with repeated explorations of the physical environment. Thus, learning about the physical world is a complex endeavor for humans and requires an extended developmental period, in comparison with the more rapid learning that occurs in species that occupy a more narrow range of physical ecologies (Gallistel, 2000). A recent study by Chen and Siegler (2000) suggests that similar processes may occur for tool use. Here, it was demonstrated that 18-month-olds have an implicit understanding of how to use simple tools (e.g., a hooked stick to retrieve a desired toy) and with experience learn to use these tools in increasingly effective ways (Gredlein & Bjorklund, 2005).

## **EVOLUTION OF GENERAL INTELLIGENCE**

In addition to knowledge about folk abilities and knowledge, an evolutionary educational psychology must incorporate the research base on general intelligence (*g*) and the underlying brain and cognitive systems. This is because performance on measures of *g* is the best single predictor of grades in school and years of schooling completed (Jensen, 1998; Lubinski, 2000; Walberg, 1984). My goal here is to provide a framework for understanding the evolution of general intelligence and the relation between these systems and the primary folk systems described above; a

more complete discussion can be found elsewhere (Geary, 2005). As I discuss in the first section, the interaction between  $g$  and folk knowledge and the associated selection pressures provide the key to understanding the uniquely human ability to adapt to variation and novelty within a lifetime and through this the ability to learn in the evolutionarily novel context of school. In the second section, I describe the core mechanisms that appear to underlie performance on measures of  $g$ , and thus the mechanisms that may have evolved to enable an experience-driven adaptation to variation in social and ecological conditions during individual lifetimes. Evolved mechanisms that enable humans to adapt to within-lifetime variation are the same mechanisms that likely contribute to the generation of novelty and culture, and that support the learning of secondary knowledge and abilities.

### **Adapting to Variation**

The key to understanding the evolution of  $g$  and plasticity in primary modular systems is the pattern of stability and change across generations and within lifetimes in the information patterns that covaried with survival or reproductive outcomes during human evolution (Geary, 2005). As noted above, the three primary categories of evolutionarily significant information are social, biological, and physical and are captured by the respective domains of folk psychology, folk biology, and folk physics. Corresponding examples of these include information patterns generated by the body shape and movement of conspecifics (Blake, 1993; Downing et al., 2001) and by species of predator and prey (Barton & Dean, 1993), as well as by environmental features (e.g., star patterns) used in navigation (Gallistel, 1990), among many other conditions. As emphasized by many evolutionary psychologists, when such information patterns are consistent from one generation to the next and stable within lifetimes, modular brain and cognitive systems that automatically direct attention to and facilitate the processing of these restricted forms of information should evolve, as illustrated by the invariant end of the continuum in Figure 1.3 (Cosmides & Tooby, 1994; Gallistel, 2000).

Built into the organization of many of these systems are implicit (i.e., below the level of conscious awareness) decision-making heuristics (e.g., Gigerenzer & Selten, 2001), that is, behavior-ecology correlations that produce functional outcomes (Simon, 1956). These cognitive “rules of thumb” represent evolved behavioral responses to evolutionarily significant conditions. In some species of bird, for example, parental feeding of chicks can be described as a simple heuristic: “Feed the smallest, if there is plenty of food; otherwise, feed the largest” (Davis & Todd, 2001).

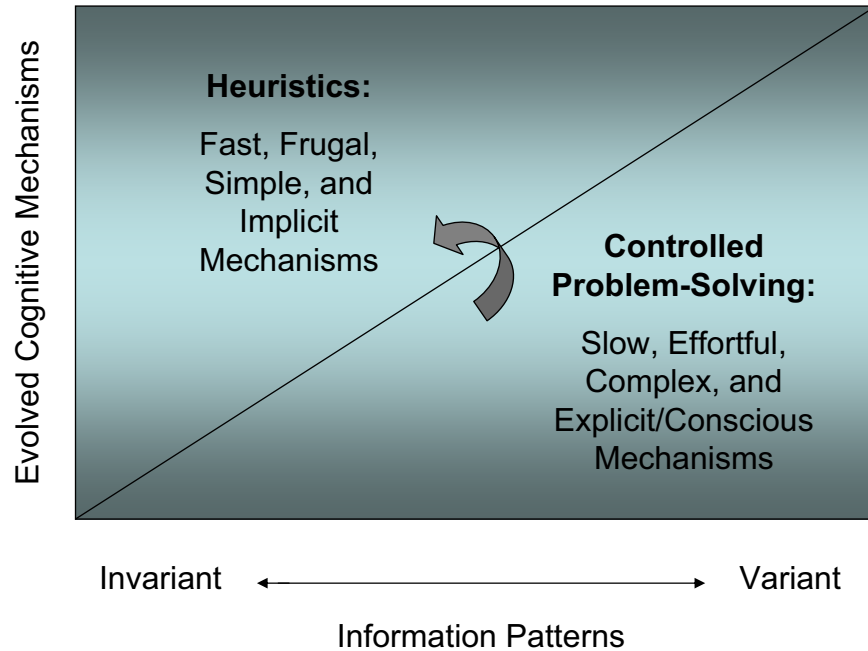


Figure 1.3. The types of cognitive mechanisms that operate on ecological or social information are predicted to vary with the extent to which that information tended to be invariant (resulting in evolved heuristics) or variant (resulting in evolved problem-solving mechanisms) during the species' evolutionary history and during a typical lifetime. From "*The origin of mind: Evolution of brain, cognition, and general intelligence*," by D. C. Geary, p. 168. Copyright 2005 by the American Psychological Association. Reprinted with permission.

There can also be conditions that influence survival and reproductive prospects but that produce less predictable, or variant, information patterns across generations and within lifetimes. This variation might involve fluctuating climatic conditions (e.g., Potts, 1998), but is most likely to emerge from the behavioral interactions between biological organisms that have competing interests (Maynard Smith & Price, 1973). Host-parasite and predator-prey dynamics, as well as social competition, are central examples of this type of relationship. For humans, variable conditions appear to be largely produced by social dynamics and some dynamics associated with ecological demands, such as hunting. In other words, aspects of social and ecological selection pressures that resulted in the evolution of the folk systems represented in Figure 1.2, also appear to have resulted in conditions that favored the evolution of less modularized,

domain-general brain and cognitive systems (Chiappe & MacDonald, 2005; Geary, 2005). As an example, in the context of competitive social relationships, novel behavior or behavioral variability provides an advantage, because it renders implicit, heuristic-based behavioral responses of competitors less effective. As shown at variant end of the continuum in Figure 1.3, these domain-general systems enable the explicit representation of variant information patterns in working memory, and support the controlled problem solving (e.g., mean-ends analysis) needed to cope with these variable conditions.

This is where *g* meets the motivation to control and integrates with more modularized systems. In particular, I recently proposed that the attentional, working memory, and problem-solving mechanisms that compose *g* (described below) evolved to support the conscious psychological representations of the perfect world, or at least a better situation, and to enable the simulation of behavioral strategies to reduce the difference between one's current situation and the achievement of this goal (Geary, 2005). The forms of information manipulated in these working memory representations are largely in the domains of folk knowledge—for example, mentally rehearsing a verbal argument to be used at a later time to pursue one's interests. But, variation at this level differs from the within-module variation discussed earlier. The modular-level plasticity evolved to accommodate variation within the restricted classes represented by the bottommost boxes in Figure 1.2 (e.g., facial expression), as in the ability to discriminate one face from another. The working memory simulations, in contrast, evolved to cope with macrolevel variation represented by the higher levels of organization in Figure 1.2 (e.g., individual, folk biology). For example, simulating the potential behavior of a friend in a future but unfamiliar situation can involve pulling together and integrating information from a variety of lower-level stores, including the person schema, and episodic memories of this individual's characteristic facial expressions, language expressions, and so forth (Kahneman & Tversky, 1982). If the interaction between two friends is simulated as they attempt to compromise on competing goals and interests, then the potential for variation in these behavioral dynamics and the potential for change in personal relationships increase substantially.

Variation at this macrolevel cannot be as strongly constrained by inherent mechanisms such as the more modular systems shown in the lower levels of Figure 1.2, because the specifics of this variation (e.g., levels of intergroup hostilities) can change substantively from one generation to the next or within a single lifetime. However, if the ability to mentally anticipate macrolevel variation—to project oneself into the future and simulate potential scenarios in working memory—increased survival or reproductive prospects during human evolution, then brain and cognitive

systems that support these mental simulations would evolve. The conditions that would lead to the evolution of these abilities (e.g., mental time travel, complex working memory simulations) are complex, nuanced, and multifaceted and full discussion is beyond the scope of this chapter (see Alexander, 1989; Flinn et al., 2005; Geary, 2005). The gist is that from the viewpoint of the motivation to control, competition with others for control resulted in a within-species arms race (Alexander, 1989; Flinn et al., 2005), possibly beginning with the ability to generate behavioral novelty and thus circumvent the heuristic-based behaviors of competitors (Geary, 2005). The process may have started with *Homo erectus*, but in any event once started it has continued and has driven the evolution of the brain and cognitive systems that enable the creation of novelty and the anticipation of novelty generated by others. My core point here is that this ability to generate and cope with novelty within the life span resulted in the ability to learn and problem solve in evolutionarily novel contexts, including schools.

### **Components of General Fluid Intelligence**

Without an understanding of the evolution of the core mechanisms that enable the generation of cognitive and behavior novelty and adaptation to variation in social and ecological conditions within the life span, we will not have a complete understanding or appreciation of the task of educating children in modern societies. The gist of the following sections is that these core mechanisms substantively overlap with the brain and cognitive systems that compose general intelligence. Because biologically secondary abilities are, by definition, novel from an evolutionary perspective, the brain and cognitive systems that compose general intelligence should be engaged when these abilities are constructed from more modularized domains.

### ***Psychometric Research***

Research in this tradition examines individual differences in performance on various forms of paper-and-pencil abilities measures, and began in earnest with Spearman's (1904) classic study. Here, groups of elementary- and high-school students as well as adults were administered a series of sensory and perceptual tasks, and were rated by teachers and peers on their in-school intelligence and out-of-school common sense. Scores on standard exams in classics, French, English, and mathematics were also available for the high-school students. Correlational analyses revealed that above average performance on one task was associated with above average performance on all other tasks, on exam scores, and for



ratings of intelligence and common sense. On the basis of these findings, Spearman (1904, p. 285) concluded “that all branches of intellectual activity have in common one fundamental function (or group of functions).” Spearman termed the fundamental function or group of functions general intelligence or *g*.

In a series of important empirical and theoretical works, Cattell and Horn (Cattell, 1963; Horn, 1968; Horn & Cattell, 1966) later argued that the single general ability proposed by Spearman should be subdivided into two equally important but distinct abilities. The first ability is called *crystallized intelligence* (*gC*) and is manifested as the result of experience, schooling, and acculturation and is referenced by over-learned skills and knowledge, such as vocabulary. The second ability is called *fluid intelligence* (*gF*), and represents a biologically-based ability to acquire skills and knowledge. In fact, human abilities can be hierarchically organized, with processes, such as *gF*, that affect performance across many domains at the top of the hierarchy, and processes and knowledge bases that are more restricted, such as computational arithmetic, at the bottom (Carroll, 1993; Thurstone, 1938).

### **Cognitive Research**

***Speed of Processing.*** Although there are details to be resolved, several important patterns have emerged from studies of the relation between speed of processing simple pieces of information, such as speed of retrieving a word name from long-term memory, and performance on measures of *g* (Hunt, 1978; Jensen, 1998). First, faster speed of cognitive processing is related to higher scores on measures of *g* (Jensen, 1982; Jensen & Munro, 1979) but the strength of the relation is moderate ( $r_s \sim 0.3$  to  $0.4$ ). Second, variability in speed of processing is also related to scores on measures of *g* ( $r_s \sim 0.4$ ; Jensen, 1992). The variability measure provides an assessment of the consistency in speed of executing the same process multiple times. Individuals who are consistently fast in executing these processes have the higher scores on measures of *g* than their less consistent peers (Deary, 2000; Jensen, 1998; Neubauer, 1997). Third, the speed with which individuals can identify very briefly (e.g., 50 ms) presented information (e.g., whether “>” is pointed left or right) is moderately correlated with *g* (Deary & Stough, 1996).

These studies suggest that intelligence is related to the speed and accuracy with which information is identified, and then processed by the associated brain and perceptual systems. The processing of this information is often implicit and results in fast and automatic responses to overlearned biologically secondary information (e.g., a written word) and presumably fast and automatic responses to the forms of information (e.g., a facial expression) described in the folk sections above. When this happens, the

information is active in short-term memory, but the individual may not be consciously aware of it.

**Working Memory.** When information cannot be automatically processed by modular and heuristic systems or through access to information stored in long-term memory, the result is an automatic shift in attention to this information (Botvinick, Braver, Barch, Carter, & Cohen, 2001). The focusing of attention results in an explicit representation of this information in working memory, and simultaneous inhibition of irrelevant information (Engle, Conway, Tuholski, & Shisler, 1995). Once represented in working memory and available to conscious awareness, the information is amendable to the explicit, controlled problem solving represented by the rightmost section of Figure 1.3. The attentional system that controls the explicit manipulation of information during problem solving is called the central executive, and the modalities in which the information is represented are called slave systems. The latter include auditory, visual, spatial, or episodic representations of information (Baddeley, 1986, 2000b).

Research on the relation between performance on working-memory tasks and performance on measures of  $g$  have focused on  $gF$  (Cattell, 1963; Horn, 1968). As Cattell (1963, p. 3) stated: "Fluid general ability ... shows more in tests requiring adaptation to new situations, where crystallized skills are of no particular advantage." In theory then, performance on measures of  $gF$  should be strongly associated with individual differences in working memory and this is indeed the case, whether the measure of  $gF$  is an IQ test (Carpenter, Just, & Shell, 1990; Conway, Cowan, Bunting, Theriault, & Minkoff, 2002; Engle, Tuholski, Laughlin, & Conway, 1999) or scores on psychometric tests of complex reasoning that are highly correlated with IQ scores (Kyllonen & Christal, 1990; Mackintosh & Bennett, 2003). The strength of the relation between performance on working memory tasks and scores on measures of reasoning and  $gF$  range from moderate ( $r_s \sim 0.5$ ; Ackerman, Beier, & Boyle, 2005; Mackintosh & Bennett, 2003) to very high ( $r_s > 0.8$ ; Conway et al., 2002; Kyllonen & Christal, 1990). On the basis of these patterns, Horn (1988) and other scientists (Carpenter et al., 1990; Stanovich, 1999) have argued that measures of strategic problem solving and abstract reasoning define  $gF$ , and the primary cognitive system underlying problem solving, reasoning, and thus  $gF$  is attention-driven working memory. The relation between speed of processing and working memory is debated (Ackerman et al., 2005; Fry & Hale, 1996) and remains to be resolved (but see below).

**Summary.** Intelligent individuals identify and apprehend bits of social and ecological information more easily and quickly than do other people; their perceptual systems process this information such that the information is activated in short-term memory more quickly and with

greater accuracy than it is for other people. Once active in short-term memory, the information is made available for conscious, explicit representation and manipulation in working memory, but this only happens for that subset of information that becomes the focus of attention; irrelevant information is readily inhibited. Once attention is focused, highly intelligent people are able to represent more information in working memory than are other people and have an enhanced ability to consciously manipulate this information. The manipulation in turn is guided and constrained by reasoning and inference making mechanisms (Stanovich, 1999). My argument is that this attention-driven ability to explicitly represent and manipulate information in working memory is a core and evolved component of the human ability to adapt to social and ecological variation within the life span and thus is central to an evolutionarily informed understanding of the learning of biologically secondary knowledge and abilities (Geary, 2005), as I discuss in the section titled Academic Learning.

### **Neuroscience Research**

**Brain Size.** Research on the relation between brain volume, as measured by neuroimaging techniques, and performance on measures of *g* has revealed a modest relation ( $r \sim 0.3$  to  $0.4$ ); the bigger the better (Deary, 2000; McDaniel, 2005; Rushton & Ankney, 1996). In one of the most comprehensive of these studies, Wickett, Vernon, and Lee (2000) examined the relations between total brain volume and performance on measures of *gF*, *gC*, short-term memory, and speed of processing. Larger brain volumes were associated with higher fluid intelligence ( $r = 0.49$ ), larger short-term memory capacity ( $r = 0.45$ ), faster speed of processing ( $r_s \sim 0.4$ ), but were unrelated to crystallized intelligence ( $r = 0.06$ ). Raz, Torres, Spencer, Millman, Baertschi, and Sarpel (1993) examined the relation between performance on measures of *gF* and *gC* and total brain volume, and volume of the dorsolateral prefrontal cortex (areas 9 & 46 in both panels of Figure 1.4), portions of the parietal cortex (e.g., areas 39 & 40 in the upper panel), the hippocampus, and several other brain regions. Higher *gF* scores were associated with larger total brain volume ( $r = .43$ ), a larger dorsolateral prefrontal cortex ( $r = .51$ ), and more white matter (i.e., neuronal axons) in the prefrontal cortex ( $r = .41$ ), but were unrelated to size of the other brain regions (see also Haier, Jung, Yeo, Head, & Alkire, 2004). Performance on the *gC* measure, in contrast, was not related to size of any of these brain regions or to total brain volume.

**Regional Activation.** Several studies have examined the brain regions that become activated or deactivated while individuals solve items on measures of *gF* (Duncan et al., 2000; J. R. Gray, Chabris, & Braver, 2003; Haier et al., 1988; Prabhakaran, Smith, Desmond, Glover, & Gabrieli,

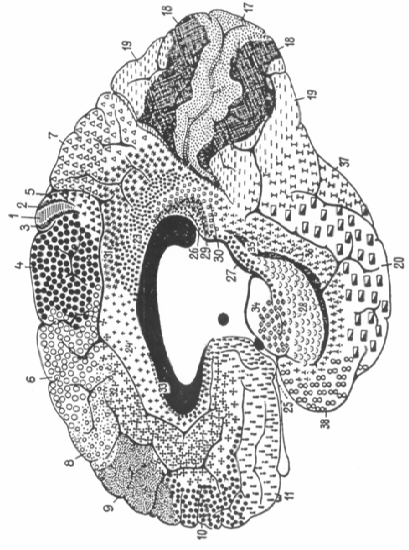
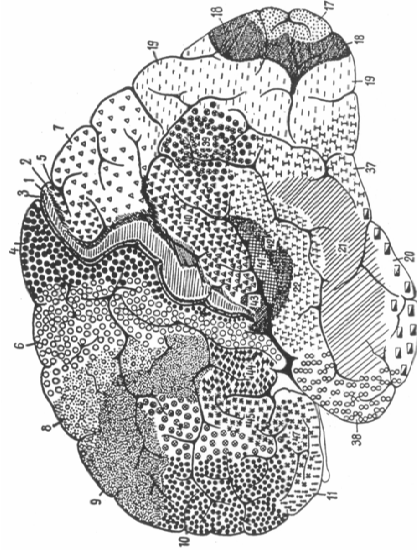
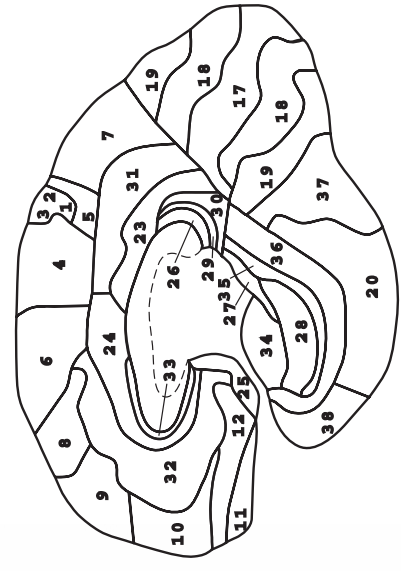
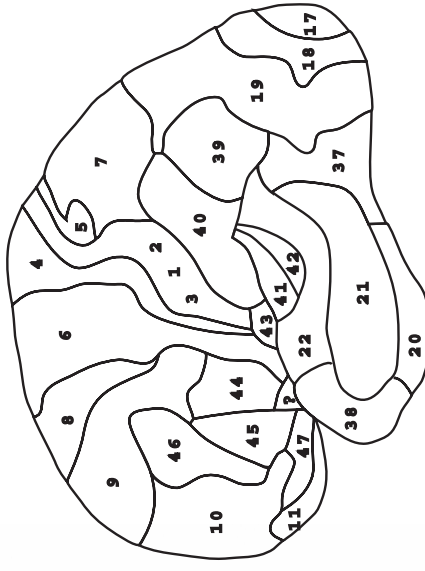


Figure 1.4. To the left, Brodmann's original map of the architectural units of the human neocortex. From *Vergleichende Lokalisationslehre der Grosshirnrinde in ihren Prinzipien dargestellt auf Grund des Zellenbaues* [Comparative localization of the cerebral cortex based on cell composition], p. 131, by K. Brodmann, 1909, Leipzig: Barth. To the right, Mark Dubin's illustration of these same areas. The top section is a lateral (outer) view of the cortex, whereas the bottom section is a medial (center, between the two hemispheres) view. Very generally, areas 1, 2, 3, 5, 31, and 43 are part of the parietal cortex and support a variety of functions including sense of body position, attention, and spatial competencies; Areas 17, 18, and 19 are part of the occipital cortex and support simple and complex visual perception; Areas 22, 41, 42, and subregions of areas 40 and 38 are part of the temporal cortex and support simple and complex auditory and speech perception; Areas 20, 21, 26-28, 34-37 and 52 are also part of the temporal lobe, but support a variety of complex visual competencies; Areas 4, 6, and 8 are involved in complex motor movements and are part of the frontal cortex; Area 44 and subregions of area 45 are involved in speech generation and are part of the frontal cortex; Areas 9, 10, 11, 25, 46, 47, and subregions of 45 are part of the prefrontal cortex and support behavioral control, executive functions, and many complex social competencies; Areas 23, 24, 30, (parts of 31), 32, and 33 are part of the cingulate and support attentional and emotional functions.

1997). These are early and pioneering studies and thus the most appropriate interpretation of their findings is not entirely certain (Deary, 2000). Nonetheless, most of the studies reveal a pattern of activation and deactivation in a variety of brain regions, much of which is likely due to task-specific content of the reasoning measures (e.g., verbal vs. visual information; K. Stephan et al., 2003). Recent studies using the imaging methods most sensitive to regional change in activation/deactivation suggest fluid intelligence may be supported, in part, by the same system of brain regions that support the working memory, attentional control, and inhibitory control components of the central executive. These areas include the dorsolateral prefrontal cortex, anterior cingulate cortex (area 24 in the lower panel Figure 1.4), and regions of the parietal cortex (Duncan et al., 2000), although size and white matter organization in other brain regions may also contribute to individual differences in *gF*.

Other studies suggest that the anterior cingulate cortex is heavily involved in achieving goals that are not readily achieved by means of heuristics (e.g., Miller & Cohen, 2001; Ranganath & Rainer, 2003). The anterior cingulate cortex in particular is activated when goal achievement requires dealing with some degree of novelty, or conflict (e.g., choosing between two alternatives). The result appears to be an automatic attentional shift to the novel or conflicted information and activation of the dorsolateral and other prefrontal areas (Botvinick et al., 2001). These areas in turn enable the explicit, controlled problem solving needed to cope with the novel situation or resolve the conflict (Kerns, Cohen, MacDonald, Cho, Stenger, & Carter, 2004). Botvinick and colleagues' proposal that novelty and conflict result in automatic attentional shifts and activation of executive functions is important, as it addresses the *homunculus* question. The central executive does not activate itself, but rather is automatically activated when heuristic-based processes—those toward the invariant end in Figure 1.3—are not sufficient for dealing with current information patterns or tasks.

### **Integration**

Although definitive conclusions must await further research, brain imaging studies on the whole support the hypothesis that the same brain systems that underlie working memory and explicit controlled problem solving are engaged when people solve items on measures of *gF* (Duncan et al., 2000; J. R. Gray et al., 2003; Kane & Engle, 2002). High scores on measures of *gF* are associated with activation of the dorsolateral prefrontal cortex, and several brain regions associated with attentional control, including the anterior cingulate cortex and regions of the parietal cortex. These same regions also appear to support the ability to inhibit irrelevant information from intruding into working memory and conscious aware-

ness (Esposito, Kirkby, van Horn, Ellmore, & Berman, 1999). Awareness of information represented in working memory and the ability to mentally manipulate this information may result from a synchronization of the prefrontal brain regions that subserve the central executive and the brain regions that process the specific forms of information (e.g., voice, face, object; Damasio, 1989; Dehaene & Naccache, 2001; Posner, 1994).

An attention-driven synchronization of the activity of dorsolateral prefrontal cortex and the brain regions that support explicit working memory representations of external information or internal mental simulations would be facilitated by faster speed of processing and rich interconnections among these brain regions. The latter are associated with larger brain size and especially a greater volume of white matter (i.e., axons). Speed of processing may be important for the synchronization process: Synchronization appears to occur through neural connections that communicate back and forth between different brain regions, creating feedback cycles. Faster speed of processing would enable more accurate adjustments in synchronization per feedback cycle. With repeated synchronized activity, the result appears to be the formation of a neural network that automatically links the processing of these information patterns (Sporns, Tononi, & Edelman, 2000). In other words, speed of processing and an attention-driven working memory system are not competing explanations of *gF* (see Ackerman et al., 2005; Engle, 2002; Kane & Engle, 2002), but rather may be coevolved and complementary mechanisms that support the conscious psychological and cognitive processes (including *gF*) that are components of the motivation to control (Geary, 2005).

More generally, I proposed that research on *gF* identified many of the core features that support the use of mental simulations as these relate to the ability to anticipate and generate behavioral responses to social and ecological conditions that are toward the variant end of the continuum in Figure 1.3 (Geary, 2005). As noted, the function of a problem-solving based manipulation of mental models is to generate strategies that will reduce the difference between conditions in the real world and those simulated in a perfect world, that is, to generate ways to gain control of important relationships and resources. The problem-solving processes, inference making, and everyday reasoning employed to devise the corresponding social and behavioral strategies are dependent on working memory, attentional control, and the supporting brain systems, along with a sense of self.

In this view, the mechanisms that support an explicit, conscious awareness of information represented in working memory evolved as a result of the same social and ecological pressures that drove the evolution of the ability to generate and use mental models, and *gF*. Self awareness is

important to the extent that one must cope with the maneuvering of other people, if other people use this same knowledge in their social strategies (Alexander, 1989; Humphrey, 1976). In other words, 100 years of empirical research on  $g$ , and especially  $gF$ , has isolated those features of self-centered mental models that are not strongly influenced by content and that enable explicit representations of information in working memory and an attentional-dependent ability to manipulate this information in the service of strategic problem solving to cope with variation and novelty within the life span. These are thus predicted to be core systems engaged in the generation of novelty and biologically secondary knowledge and when learning secondary knowledge generated by others, as illustrated in the section titled Human Intellectual History and the Creation of Culture.

Cattell's (1963) and Horn's (1968) definition of fluid intelligence and subsequent research on the underlying cognitive and brain systems are consistent with this view: There is considerable overlap in the systems that support self-centered mental models and those that support fluid abilities (e.g., Duncan et al., 2000). One important difference between  $gF$  and these mental models is self-awareness, which is a core feature of my proposal but is not assessed on measures of fluid intelligence (Geary, 2005). If  $gF$  evolved to support use of mental simulations and their use was driven in large part by the need to cope with social dynamics, then measures of  $gF$  might be expected to include items that assessed social dynamics and awareness of these dynamics vis-à-vis one's self-interest. The reasons for the discrepancy are (a) because the initial development and goal of intelligence tests was to predict academic performance (Binet & Simon, 1916), that is, the ability to learn in the evolutionarily novel context of school, and not to cope with social dynamics. In addition: (b)  $gF$  represents the mechanisms that support content-free problem solving, and thus social items are not necessary.

### ***Modularity and Crystallized Intelligence***

In the most comprehensive review of the psychometric literature ever conducted, Carroll (1993, p. 599) concluded that most of the psychometric tests that index  $gC$  "involve language either directly or indirectly." Included among these are tests of vocabulary, listening comprehension, word fluency, reading, and spelling. The two latter skills are taught in school, as are some of the other competencies that index crystallized intelligence, such as arithmetic, and mechanical abilities. General cultural knowledge is also an indicator of  $gC$ , as are some measures of spatial and visual abilities. In total, these tests appear to tap a many of the modular domains shown in Figure 1.2, in particular language and spatial representation. They do not appear to tap all of these domains, but this is poten-



tially because not all of the modular competencies have been assessed. When other modular competencies are measured and correlated with intelligence, there is a relation. Legree (1995), for instance, found that scores on tests of knowledge of social conventions and social judgments are positively correlated with scores on measures of *g*. In others words, I am suggesting that the inherent knowledge represented in the modular systems defines one class of crystallized intelligence, *gC*-primary. The other class is represented by the knowledge (e.g., facts, procedures) learned during a lifetime through formal or informal instruction, or just incidentally, as proposed by Cattell (1963), *gC*-secondary.

### **ACADEMIC LEARNING**

My proposal is that the evolution of *gF* combined with some degree of plasticity in primary modular systems opened the door to the ability to develop evolutionarily novel, biologically secondary knowledge and abilities in school and in other cultural settings, such as the work place (Geary, 1995; Rozin, 1976). There is, however, a cost to this extraordinary ability to create novel secondary competencies and thus human culture: During the last several millennia, because the cross-generational accumulation of cultural knowledge and artifacts, such as books, has occurred at such a rapid pace (Richerson & Boyd, 2005), the attentional and cognitive biases that facilitate the fleshing out of primary abilities during children's natural activities do not have evolved counterparts to facilitate the learning of secondary abilities. In the first section, I explore the basic implications for schooling and the accumulation of cultural knowledge. In the second and third sections, I provide discussion and hypotheses regarding the potential motivational and cognitive mechanisms, respectively, that may contribute to the acquisition of secondary abilities.

### **Foundations of Evolutionary Educational Psychology**

I begin with the basic premises and principles of evolutionary educational psychology, which are elaborations and refinements of previous work (Geary, 2002a). I then attempt to frame aspects of human intellectual history and the creation of secondary knowledge as this relates to our understanding of primary folk domains. This frame provides a segue into a later discussion of potential motivational and cognitive mechanisms underlying secondary learning.

### ***Premises and Principles***

Evolutionary educational psychology is the study of the relation between folk knowledge and abilities and accompanying inferential and attributional biases as these influence academic learning in evolutionarily novel cultural contexts, such as schools and the industrial workplace. The fundamental premises and principles of this discipline are presented in Table 1.1. The premises restate the gist of the previous sections, specifically: that (a) aspects of mind and brain have evolved to draw the individuals' attention to and facilitate the processing of social, biological, physical information patterns that covaried with survival or reproductive outcomes during human evolution (Cosmides & Tooby, 1994; Geary, 2005; R. Gelman, 1990; Pinker, 1997; Shepard, 1994; Simon, 1956); (b) although plastic to some degree, these primary abilities are in part inherently constrained because the associated information patterns tended to be consistent or invariant across generations and within lifetimes (e.g., Caramazza & Shelton, 1998; Geary & Huffman, 2002); (c) other aspects of mind and brain evolved to enable the mental generation of potential future social, ecological, or climatic conditions and enable rehearsal of behaviors to cope with variation in these conditions, and are now known as *gF* (including skill at everyday reasoning/problem solving; Chiappe & MacDonald, 2005; Geary, 2005; Mithen, 1996); and (d) children are inherently motivated to learn in folk domains, with the associated attentional and behavioral biases resulting in experiences that automatically and implicitly flesh out and adapt these systems to local conditions (R. Gelman, 1990; R. Gelman & Williams, 1998; S. Gelman, 2003).

The principles in the bottom section of Table 1.1 represent the foundational assumptions for an evolutionary educational psychology. The gist is knowledge and expertise that is useful in the cultural milieu or ecology in which the group is situated will be transferred across generations in the form of cultural artifacts, such as books, or learning traditions, as in apprenticeships (e.g., Baumeister, 2005; Boyd & Richerson, 2005; Flinn, 1997; Mithen, 1996). Across generations, the store of cultural knowledge accumulates and creates a gap between this knowledge base and the forms of folk knowledge and abilities that epigenetically emerge with children's self-initiated activities. There must of course be an evolved potential to learn evolutionarily novel information and an associated bias to seek novelty during the developmental period and indeed throughout the life span; this may be related to the openness to experience dimension of personality (Geary, 1995). However, the cross-generational accumulation of knowledge across cultures, individuals, and domains (e.g., people vs. physics) has resulted in an exponential increase in the quantity of secondary knowledge available in modern

← Au: Boyd & Richerson 2005 not listed in refs. Should this be Richerson & Boyd?

**Table 1.1. Premises and Principles  
of Evolutionary Educational Psychology**

<b>Premises</b>	
1.	Natural selection has resulted in an evolved motivational disposition to attempt to gain access to and control of the resources that have covaried with survival and reproductive outcomes during human evolution.
2.	These resources fall into three broad categories; social, biological, and physical which correspond to the respective domains of folk psychology, folk biology, and folk physics.
3.	Attentional, perceptual, and cognitive systems, including inferential and attributional biases, have evolved to process information in these folk domains and to guide control-related behavioral strategies. These systems process restricted classes of information associated with these folk domains.
4.	To cope with variation in social, ecological, or climatic conditions, systems that enabled the mental generation of these potential future conditions and enabled rehearsal of behaviors to cope with this variation evolved and the supporting attentional and cognitive mechanisms are known as general fluid intelligence and everyday reasoning.
5.	Children are biologically biased to engage in activities that recreate the ecologies of human evolution; these are manifested as social play, and exploration of the environment and objects. The accompanying experiences interact with the inherent but skeletal folk systems and flesh out these systems such that they are adapted to the local social group and ecology.
<b>Principles</b>	
1.	Scientific, technological, and academic advances initially emerged from the cognitive and motivational systems that support folk psychology, folk biology, and folk physics. Innovations that enabled better control of ecologies or social dynamics or resulted in a coherent (though not necessarily scientifically accurate) understanding of these dynamics are likely to be retained across generations as cultural artifacts (e.g., books) and traditions (e.g., apprenticeships). These advances result in an ever growing gap between folk knowledge and the theories and knowledge base of the associated sciences and other disciplines (e.g., literature).
2.	Schools emerge in societies in which scientific, technological, and intellectual advances result in a gap between folk knowledge and the competencies needed for living in the society.
3.	The function of schools is to organize the activities of children such that they acquire the biologically secondary competencies that close the gap between folk knowledge and the occupational and social demands of the society.
4.	Biologically secondary competencies are built from primary folk systems and the components of fluid intelligence that evolved to enable individuals to cope with variation and novelty.
5.	Children's inherent motivational bias to engage in activities that will adapt folk knowledge to local conditions will often conflict with the need to engage in activities that will result in secondary learning.
6.	The need for explicit instruction will be a direct function of the degree to which the secondary competency differs from the supporting primary systems.

societies today. For most people, the breadth and complexity of this knowledge will very likely exceed any biases to learn in evolutionary novel domains.

A related issue concerns the traits that enable the *creation* of biologically secondary knowledge and thus culture and the extent to which these traits overlap with the ability to *learn* knowledge created by others. Stated differently, Is the goal of education to have children recreate the process of discovery, to learn the products of discovery, or some combination? Some educators have advocated a focus on the process of discovery without full consideration of the constellation of traits and opportunity that contribute to the creation of secondary knowledge (e.g., Cobb, Yackel, & Wood, 1992). In fact, research on creative-productive individuals suggests that the full constellation of traits that facilitate the discovery and creation of secondary knowledge is rare and not likely reproducible on a large scale (Simonton, 1999a, 1999b, 2003; Sternberg, 1999; Wai, Lubinski, & Benbow, 2005), although there is likely to be overlap between the traits that enable both the creation and the learning of secondary knowledge. My proposal is that this overlap includes the cognitive and conscious psychological mechanisms that support the motivation to control, that is, the working memory and attentional components of *gF*. In the following sections, I hope to illustrate the complexity of the discovery process and at the same time provide suggestions as to how primary folk knowledge may form the foundation for the creation and learning of secondary knowledge, and to provide a contrast of primary and secondary knowledge.

### ***Human Intellectual History and the Creation of Culture***

Scientific, technological, and academic domains (e.g., poetry) emerged from an interplay of cultural wealth, opportunity, and a combination of traits in the individuals who made advances in these domains (Murray, 2003; Simonton, 2003). Murray found that historical bursts of creative activity (as with the Renaissance or industrial revolution) tended to emerge in wealthier cultures with mores that did not severely restrict individual freedom and that socially and financially rewarded creative expression. Studies of exceptional accomplishments suggest they tend to be generated by individuals situated in these cultures and with a combination of traits that include high general fluid intelligence, creativity (e.g., ability to make remote associations), an extended period of preparation (about 10 years) in which the basics of the domain are mastered, long work hours (often > 60/week), advantages in certain folk domains, ambition, and sustained output of domain-related products, such as scientific publications (see Ericsson, Krampe, & Tesch-Römer, 1993; Lubinski, 2004; Sternberg, 1999). These components of exceptional accomplishment can be used to illustrate the interplay between folk knowledge, fluid intelligence, motivation, and the generation of secondary knowledge, and to illustrate why children's intuitive folk knowledge and learning biases are not sufficient for secondary learning; implications for understanding

individual differences are discussed in the section titled Individual Differences in Secondary Learning.

In other words, I am suggesting that human intellectual history and the emergence of scientific and academic domains, as well as other forms of cultural knowledge (e.g., literature), was possible only after the evolution of the conscious psychological and cognitive mechanisms—components of fluid intelligence—that support the motivation to control. These secondary domains initially coalesced around the areas of folk psychology, folk biology, and folk physics, because these represent areas of inherent interest to human beings and because human beings have built-in biases to organize knowledge in these domains. Academic disciplines in universities, for instance, seem to fall into these three categories, with humanities and the social sciences related to folk psychology; biology, zoology, forestry, and medicine related to folk biology; and, much of mathematics as well as physics and engineering related to folk physics. Of course, at this point in our history the knowledge bases in these domains far exceed knowledge implicit in folk systems, but the interests of individuals who pursue training in these different academic disciplines differ in ways consistent with folk-related motivational biases.

People who pursue careers in the humanities and social sciences tend to be interested in people and social relationships, whereas people who pursue careers in mathematics and the physical sciences tend to be interested in nonliving physical phenomena and abstract theory (Lubinski, 2000; Roe, 1956; Wai et al., 2005), as elaborated in the subsection titled Evolved Interests and Occupational Niches. These may be a reflection of motivational and affective biases that are respective components of folk psychology and folk physics. Consistent with these differences in interests, there may be an accompanying elaboration of associated primary knowledge and abilities. For instance, there is preliminary evidence that some eminent mathematicians and physical scientists may have an enhanced understanding of folk physics, but below average competencies in the domain of folk psychology (Baron-Cohen, Wheelwright, Stone, & Rutherford, 1999). In any case, in the following sections, I illustrate how the creation of secondary knowledge may interact with folk biases, and why the creation of this knowledge may be dependent on the cognitive and conscious psychological representations associated with the motivation to control and *gF*.

***Scientific Physics and Folk Physics.*** The scientific domain of physics is one of humanity's most significant intellectual accomplishments and yet is a domain that is remote from the understanding of most of humanity. One reason for this is that people's naïve understanding of certain physical phenomena is influenced by the inferential biases that appear to be an aspect of folk physics but differ from the scientific understanding of the

same phenomena (McCloskey, 1983). For instance, when asked about the forces acting on a thrown baseball, most people believe there is a force propelling it forward, something akin to an invisible engine, and a force propelling it downward. The downward force is gravity, but there is in fact no force propelling it forward, once the ball leaves the player's hand (Clement, 1982). The concept of a forward-force, called "impetus", is similar to pre-Newtonian beliefs about motion prominent in the fourteenth to sixteenth centuries. The idea is that the act of starting an object in motion, such as throwing a ball, imparts to the object an internal force—impetus—that keeps it in motion until this impetus gradually dissipates. Although adults and even preschool children often describe the correct trajectory for a thrown or moving object (e.g., Kaiser, McCloskey, & Proffitt, 1986), reflecting their implicit folk competences, their explicit explanations reflect this naïve understanding of the forces acting upon the object.

Careful observation, use of the scientific method (secondary knowledge itself), and use of inductive and deductive reasoning, are necessary to move from an intuitive folk understanding to scientific theory and knowledge. In his masterwork, the *Principia* (1995, p. 13), Newton said as much: "I do not define time, space, place and motion, as being well known to all. Only I must observe, that the vulgar conceive those quantities under no other notions but from the relation they bear to sensible objects." In other words, the "vulgar" among us (myself included) only understand physical phenomena in terms of folk knowledge and Newton intended to and did go well beyond this. Newton corrected the pre-Newtonian beliefs about the forces acting on objects, but still appears to have relied on other aspects of folk physical systems to complete this work. Newton's conceptualization of objects in motion and the gravitational and rectilinear forces underlying the pattern of this motion were based on his ability to explicitly use visuospatial systems to construct geometric representations of motion and then to apply Euclidean geometry and formal logic to mathematically prove the scientific accuracy of these representations. The explicit and exacting use of formal logic is associated with high general fluid intelligence (Stanovich, 1999). In addition, Newton devoted an extended period of sustained effort and attention to this work (e.g., Berlinski, 2000). In fact, Newton has been described as being obsessed with understanding physical phenomena and spent many years thinking about these phenomena and conducting experiments to test his hypotheses, at a cost to social relationships.

Although a functional relation can only be guessed, it is of interest that areas of the neocortex that are typically associated with spatial imagery and other areas of folk physics (i.e., the parietal lobe) were unusually large (area 40 in the upper panel of Figure 1.4) in Albert Einstein's brain (Witel-

son, Kigar, & Harvey, 1999). In response to a query by Hadamard (1945) as to how he approached scientific questions, Einstein replied:

The words of the language as they are written or spoken, do not seem to play any role in my mechanism of thought. The psychical entities which seem to serve as elements in thought are certain signs and more or less clear images which can be “voluntarily” reproduced and combined.... There is, of course, a certain connection between those elements and relevant logical concepts. (Hadamard, 1945, p. 142)

Hadamard (1945, p. 143) also noted that Einstein “refers to a narrowness of consciousness,” which appears to have referred to sustained attention and the inhibition of distracting information while working on scientific questions, which are components of *gF*. Einstein’s accomplishments are, of course, unusual, but his descriptions of how he achieved some of his insights are of interest, because they are consistent with an attention-driven use of mental simulations—the conscious psychological systems—and a reliance on the modular systems that support folk physics. It is of interest that a similar pattern of brain morphology and enhanced visuospatial abilities combined with relatively poor language abilities has been identified in an extended family and appears to be heritable (Craggs, Sanchez, Kibby, Gilger, & Hynd, in press; see also Gohm, Humphreys, & Yao, 1998). In any event, Einstein’s discoveries and those of many other twentieth century physicists further widened the gap between folk physics and scientific physics, and in doing so greatly complicated the task of teaching modern physics.

***Scientific Biology and Folk Biology.*** In the eighteenth century, the early and largely accurate (scientifically) classification systems of naturalists, especially that of Linnaeus (i.e., Carl von Linné; cf. Frängsmyr, 1983), were almost certainly based on the same implicit knowledge base and inferential biases that define folk biology, as this Western system for classifying flora and fauna is very similar to the systems found in traditional populations (Berlin et al., 1973). An important difference is that Linnaeus’ binomial (genus, species) taxonomy included more than 12,000 plants and animals and was constructed in a *conscious, explicit* (rules for classification were codified) and *systematic* manner in comparison to the more *implicit* organization of folk biological knowledge that is found in people living in natural ecologies (Atran, 1998); the latter is reflected in the way in which individuals of these societies organize examples of different species. Of course, these early scientific taxonomies continue to the expanded and refined, and most recently informed by genetic analyses of the relationships among species (e.g., Liu et al., 2001). Again, the gap between folk and scientific knowledge continues to widen.

**Mathematics and Folk Physics.** In an early article (Geary, 1995), I proposed that the development of geometry—the study of space and shape—as a formal discipline might have been initially influenced by early geometers’ ability to explicitly represent the intuitive folk physical knowledge implicit in the perceptual and cognitive systems that evolved for navigation in three-dimensional space (Dehaene, Izard, Pica, & Spelke, 2006; Shepard, 1994). For instance, in the refinement and integration of the basic principles of classic geometry, Euclid (1956) formally and explicitly postulated that a straight line can be draw from any point to any point—that is, the intuitive understanding that the fastest way to get from one place to another is to go “as the crow flies” was made explicit in a formal Euclidean postulate. Using a few basic postulates and definitions, Euclid then systematized existing knowledge to form the often complex and highly spatial components of classic geometry. Achievement of this feat must have also required high general intelligence and an exceptional ability to maintain attentional focus. A potentially important difference between geometry and physics is that Euclid’s five postulates and 23 definitions are very basic, defining lines, circles, angles, and shapes, and thus not prone to the naïve attributional errors common in people’s description of physical phenomena. This difference may help to explain the more than 1,700 year gap between Euclid’s *The elements* published circa 30 BC and the 1687 publication of Newton’s *Principia*.

**Scientific Problem Solving.** The emergence of the biological sciences provides an example of the importance of goal-directed and explicit problem solving, among other factors, for scientific discovery. These examples illustrate the complexity of these tasks, the confluence of experiences and individual traits needed for scientific advances, and the accumulation of secondary knowledge, and they may also inform research and debate on the teaching of the scientific method and scientific reasoning, as I discuss in the section titled Evolution and Science Education. Important differences, for instance, between instruction of science and scientific discovery include the size of the problem space—the operators (e.g., rules for change in the domain) and assumptions that influence how a problem can be solved (Newell & Simon, 1972)—and the ill-structured nature of problems confronting working scientists (Klahr & Simon, 1999). An example of the latter is provided by various attempts to discover the mechanisms responsible for the origin of species (Desmond & Moore, 1994; Raby, 2001). This was an ill structured problem in that the solution required knowledge that spanned many domains (e.g., the fossil and geological records), and the knowledge and operators needed to ultimately solve the problem were not known.

In the first half of the nineteenth century and before this time, most naturalists, such as the renowned paleontologist Owen (1860), assumed



the origin of species was driven by some form of divine intervention (Ospovat, 1981). This assumption was crucial because it defined the problem space and the relevant operations and knowledge (e.g., scripture) that could be applied in attempts to solve the problem. Owen's assumption of divine intervention placed legal operators that involved material causes and thus the actual mechanisms involved in the origin of species outside of the problem space and thus rendered the problem unsolvable. Darwin and Wallace, in contrast, assumed the origin of species was due to material causes acting in nature (J. Browne, 2002; Darwin, 1846; Desmond & Moore, 1994; Raby, 2001). The relevant knowledge was not scripture but rather arose, in part, from intuitive folk biological knowledge and motivational biases as these were applied to extensive observations of nature *and* as elaborated by relevant secondary knowledge, including Lyell's (1830) *Principles of geology*. Of particular importance was Lyell's inference regarding patterns in the fossil record (1839, p. 161):

It appears, that from the remotest periods there has been ever a coming in of new organic forms, and an extinction of those which pre-existed on the earth; some species having endured for a longer, others for a shorter time; but none having ever re-appeared after once dying out. The law which has governed the creation and extinction of species [is not known].

The observations and hypotheses of Malthus (1798) also contributed greatly to Darwin and Wallace's goal-relevant knowledge and to the construction of the mechanisms of natural selection. Malthus' monograph described a pattern of oscillating expansions and contractions of the size of human populations in preindustrial Europe and in other regions of the world. Expansions often continue beyond the carrying capacity of the supporting resources, at which point the population crashes. The crashes represent a sharp increase in mortality, largely due to famine, epidemics, and conflicts with other people (e.g., wars) over control of land and other life-supporting resources, in keeping with the discussion in subsection titled Motivation to Control. The increased mortality reduces the population to a level below carrying capacity, that is, to a point where there are once again excess resources, and thus another cycle of population expansion ensues. With respect to Malthus' description, Wallace noted in a letter written in 1887 and reprinted in Darwin's autobiography (F. Darwin, 2000, pp. 200-201):

This had strongly impressed me, and it suddenly flashed upon me that all animals are necessarily thus kept down—"the struggle for existence"—while *variations*, on which I was always thinking, must necessarily often be *beneficial*, and would then cause those varieties to increase while the injurious variations diminished. (*italics in original*)

An illustration of Wallace's *explicit* reasoning about the origin of species before this insight is provided in an 1855 (p. 184) article titled, "On the Law Which Has Regulated the Introduction of New Species." In this article he proposed the following hypothesis, "*Every species has come into existence coincident both in space and time with a pre-existing closely allied species*" (p. 186, italics in original). In other words, new species arise from extant species. Induction—formulating a general principle based on observable facts—played an important part in Wallace's formulation of this conclusion. During his expeditions in the Amazon and throughout Malaysia, Wallace (1855, p. 189) observed that there is a pattern in the geographic distribution of species, "closely allied species in rich groups being found geographically near each other, is most striking and important." He also described how the same pattern is evident in the fossil record. When this pattern was combined with deductions based on a number of premises and facts described in the article, Wallace concluded that related species (e.g., of butterflies) are found in the same geographic location because they all arose from a common ancestor that resided in this location. Wallace further concluded that the creation of new species from existing species "must be the necessary results of some great natural law" (p. 195). Wallace discovered the great natural law—natural selection—3 years later, when he linked Malthus' (1798) observations to the earlier noted favorable and unfavorable variations in traits (Darwin & Wallace, 1858).

In addition to reading Lyell (1830) and Malthus (1798)—cultural artifacts that preserved the insights of earlier generations—Darwin (1846) and Wallace (1855) acquired goal relevant knowledge through their extensive collecting and taxonomically organizing species of many different kinds, and through years of careful observation of these species in natural ecologies. Despite Wallace's statement that the mechanisms of natural selection "suddenly flashed upon me," it is clear that he explicitly formulated the goal of discovering these mechanisms at least 13 years before this insight (Raby, 2001). Similarly, Darwin's understanding of these mechanisms was refined between 1838 and 1856-1857 (Ospovat, 1979, 1981). Nonetheless, it is likely the case that aspects of this process of discovery occurred "unconsciously," that is, through associations that developed implicitly and only at times explicitly entered working memory for conscious evaluation (Simonton, 2004).

My points are that the discovery of the mechanisms of natural selection (1) was built on explicit and biologically secondary knowledge (e.g., documentation of the fossil record) generated by other naturalists and transferred across generations; (2) the knowledge base needed to make this discovery was extensive and required years of study, reflection, and experience; and (3) the discovery of natural selection itself emerged from a confluence of factors interacting with this knowledge base. These factors

include the explicit goal of discovering these mechanisms, the ability to explicitly problem solve within an ill-structured problem space, and an intense interest in the natural world. Again, the discovery extended and thus further widened the gap between folk biology and the science of biology.

### **Implications**

One consequence of scientific, technological, and other cultural (e.g., accumulation of literature) advances is a widening of the gap between folk knowledge and abilities and the secondary knowledge and abilities needed to live successfully in the cultures in which these advances emerge. The most basic and critical implication for education is that folk knowledge and abilities, though necessary, are no longer sufficient for occupational and social functioning (e.g., understanding interest on debt) in modern society (Geary, 1995). The educational issues are multifold and not fully understood at this time. In the follow sections, I outline some of the core issues that will confront an evolutionarily informed approach to education, and provide suggestions for future theoretical and empirical research related to these issues. I begin with the issue of children's motivation to learn in school and then proceed to issues related to potential mechanisms involved in transforming primary knowledge and abilities into culturally-useful secondary knowledge and abilities. *The gist is that the cognitive and motivational complexities of the processes involved in the generation of secondary knowledge and the ever widening gap between this knowledge and folk knowledge leads me to conclude that most children will not be sufficiently motivated nor cognitively able to learn all of secondary knowledge needed for functioning in modern societies without well organized, explicit and direct teacher instruction.* (As I discuss in the section titled Individual Differences in Secondary Learning, one exception might be children with high gF.)

### **Motivation to Learn**

The evolution of gF and the ability to adapt to social and ecological variation within the life span likely coevolved with the expansion of human childhood and adolescence and with the exquisite human ability to learn during this period of development. The latter is a necessary component of our ability to transfer culturally accumulated knowledge from one generation to the next (Boyd & Richerson, 2005; Flinn, 1997; Henrich & McElreath, 2003; Scarr, 1993). The most fundamental mechanisms of transferring this knowledge include use of stories to convey morals (i.e., cultural rules for social behavior) and other themes relevant to day-to-day living, and apprenticeships, that is, learning culturally important

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skills (e.g., hunting, tool making) through observation of or direct instruction by more skilled individuals (Brown, 1991). The content of stories and apprenticeships is predicted to be centered on features of social dynamics or the ecology that tend to vary within life spans and for which the ability to adapt to this variation resulted in social or reproductive advantage during human evolution (Geary, 2005). In addition to the mechanisms that support social learning (e.g., observational learning; Bandura, 1986), children's adaptation to this variation is predicted to be dependent on implicit perceptual and affective biases that direct attention to and facilitate the ability to learn in these domains. The latter would include domain-specific abilities, as in quickly and implicitly learning to discriminate one person from another (e.g., Kisilevsky et al., 2003), as well as learning to use gF to deal with more dynamic situations.

Individual differences in children's and adults' biases toward some aspects of their social or ecological world more than other aspects are also predicted to evolve. These individual differences are common across species (Gosling, 2001), and may be particularly important for species that live in large and complex social groups; these groups are an important context within which evolutionary selection occurs (Alexander, 1989). Among the benefits of individual differences, and the resulting niche specialization and division of labor, are reduced competition and increased reciprocal dependence among members of the in-group (Baumeister, 2005). Moreover, the ability to learn during the lifetime, niche specialization, and the tendency of humans to imitate successful individuals create a social context with several specific benefits. First, at a relatively low cost and by means of social learning many individuals can acquire some of the basic competencies of the most skilled individuals in different niches (e.g., social leadership to tool making). Second, as group size increases and especially as the wealth of the society increases (Murray, 2003), there is opportunity for a small number of very skilled individuals—those having the traits described in the section titled Human Intellectual History and the Creation of Culture—to become creative-productive innovators in their niche (Bjorklund, *in press*; Bjorklund & Pellegrini, 2002; Flinn, 1997; Henrich & McElreath, 2003). These are the individuals who provide the most novel solutions to problems that arise from social and ecological variation, solutions that can benefit their group and are imitated by other people.

We are thus confronted with two core issues. The first concerns species-typical biases in children's ability to learn in one domain or another and their corresponding motivational and conative preferences, and the second concerns individual differences within the species-typical range. The implications for how these biases influence learning in school and in other evolutionarily novel contexts are not well articulated at this time.

My goal for the next two sections is to place these conative and motivational biases in an evolutionary perspective; learning biases are addressed in *Biologically Secondary Learning*. In the first section, I make predictions regarding potential inherent conative and interest biases, and in the second section I discuss these biases in the context of contemporary models of children's academic interests and achievement motivation (Bandura, 1993; Eccles, Wigfield, Harold, & Blumenfeld, 1993; Grant & Dweck, 2003; Wigfield & Eccles, 2000).

### ***Motivation to Control and Folk Domains***

It follows from the motivation to control model that all individuals will attempt to organize their world in ways that are most "comfortable" for their phenotype. This statement is keeping with other evolutionary predictions (e.g., Trivers, 1974), and with developmental (e.g., Scarr, 1996; Scarr & McCartney, 1983) and behavioral genetic (Bouchard et al., 1996; Plomin, DeFries, & Loehlin, 1977) theory and research (e.g., Jennings, 1975; Kagan, 1998; Lever, 1978). There are individual differences in children's reactivity to social and other stimuli and in self-directed niche seeking, but all normally developing children attempt to exert some type of control in their social relationships and in other contexts. The difference between my predictions and those of other models are in terms of specificity; that is, children's self-directed activities and interests will coalesce around the social and ecological domains outlined in Figure 1.2. The activities would include, for instance, competitive group formation, formation of dyadic relationships, and object exploration. My goal here is to provide a framework for understanding how these evolved motivational and conative biases might be expressed in the context of modern society. To anchor these biases in society, I start with empirical research on occupational interests and then move to children's activity preferences.

***Evolved Interests and Occupational Niches.*** I began with the assumption that evolved motivational and conative biases, as well as dimensions of personality, influence niche seeking in school and in later occupational choices. If this assumption is correct, then these biases will emerge on measures of occupational interests (e.g., Achter, Lubinski, Benbow, & Eftekhari-Sanjani, 1999; Ackerman, 1996; Ackerman & Heggstad, 1997; Campbell & Holland, 1972; G. D. Gottfredson, Jones, & Holland, 1993; Holland, 1996; Lubinski, 2000; Lubinski & Benbow, 2000; Prediger, 1982; Roe & Klos, 1969; Strong, 1943; Wai et al., 2005). In examining this prediction, I started with Holland's (1966) influential and highly useful hexagon of occupational interests, that is, realistic, investigative, artistic, social, enterprising, and conventional (RIASEC), as shown in Figure 1.5. Factor analytic and other approaches suggest that two more basic dimensions underlie the distribution of these occupational interests, that is, peo-

ple/things and data/ideas (Lubinski & Benbow, 2000; Prediger, 1982). As shown by the arrows in Figure 1.5, I labeled the latter concrete/abstract to make the dimension less specific to occupational settings. The basic point is that individuals differ in the extent to which they prefer to engage in concrete activities or think about abstract ideas.

I then examined the preferred activities and types of occupations that clustered in different areas of Holland's hexagon and along the people/things, concrete/abstract dimensions (Campbell & Holland, 1972; Harmon, Hansen, Borgen, & Hammer, 1994). Campbell and Holland, for instance, found that Realistic occupations include machinists, tool makers, foresters, and farmers; Investigative occupations include physical scientists, experimental psychologists, mathematicians, biologists, and engineers; Artistic occupations include actors, artists, musicians, and architects; Social occupations include counselors, ministers, secretaries, and teachers; Enterprising occupations include sales people, business managers, and lawyers; and Conventional occupations include bankers, office workers, and accountants. The bias toward people versus things is

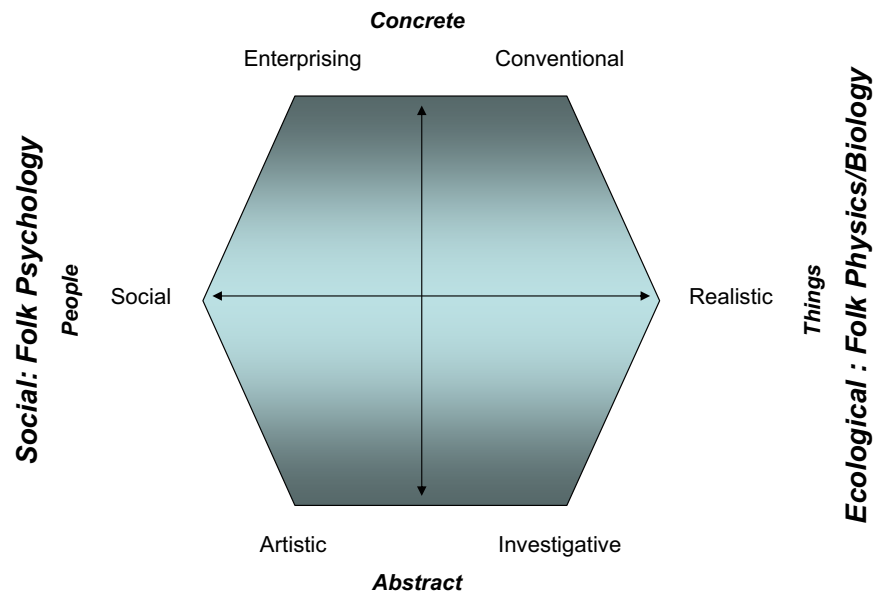


Figure 1.5. Holland's (1996) model of occupational interests, underlying dimensions of basic interests (people/things, concrete/abstract), and potential relation to folk domains. Adapted from "States of excellence" by D. Lubinski & C. P. Benbow, 2000, *American Psychologist*, 55, p. 140.

evident across these occupational clusters and was suggested by Roe and Klos (1969, p. 92) as an “orientation to interpersonal relations vs. natural phenomena.” The concrete pole of the concrete/abstract dimension reflects a focus on social (enterprising) or material (conventional) economic activities—those that produce income or other tangible resources (e.g., food in traditional societies)—whereas the abstract pole represents a focus on the symbolic representation and explanation of social and personal experience as well as natural phenomena, as I elaborate below.

Roe and Klos’ (1969) casting of the people/things dimension in terms of interpersonal versus natural phenomena maps onto the broad social and ecological domains shown in Figure 1.2 and represented in bold italics in Figure 1.5. In other words, human interests are predicted to map onto the proposed folk domains shown in Figure 1.2, and individual differences in these interests are predicted to span from highly social (folk psychology) to highly interested in how to use objects as tools (folk physics). The prediction of individual differences emerges from the above-noted benefits of niche specialization and a division of labor. If this prediction is correct, then individual differences in niche-related interests and corresponding abilities and personality should co-evolve and cluster in folk domains. One testable empirical prediction is that an interest in things will be associated with enhanced folk physical and folk biological competencies and an interest in people will be associated with enhanced folk psychological competencies, and higher extraversion on measures of personality. Although cause-effect cannot be determined, Ackerman and Heggestad’s (1997) analysis of the relations among interests, abilities, and personality provides some supporting evidence (see also L. Larson, Rottinghaus, & Borgen, 2002; Ozer & Benet-Martínez, 2006).

Individuals with strong realistic interests, that is, an interest in things, tend to have good mechanical and spatial abilities, but are often weaker on verbal abilities (Ackerman & Heggestad, 1997; Gohm et al., 1998). Individuals with strong investigative interests tend to be strong on mathematical (i.e., abstract) reasoning, and often have good spatial/mechanical abilities. Individuals with conventional interests tend to have strong perceptual-motor skills, that is, they are fast and efficient on tasks that involve the organization and manual manipulation of physical objects. The enhanced spatial and mechanical interests and abilities of many individuals in realistic and investigative occupations and the working with materials for economic reasons associated with conventional occupations are consistent with the prediction that these have been built upon an evolved folk physics. An interest in nature and in biological occupations also falls in the realistic/investigative area of Holland’s hexagon (Harmon et al., 1994), but corresponding abilities in these areas (e.g., for taxonomically organizing species) are not typically assessed psychometrically and

thus the relation between these interests and theoretically important abilities was not included in Ackerman and Heggestad's analysis. Nonetheless, these interests are consistent with an evolved folk biology.

The people orientation is associated with social and enterprising interests and to a lesser extent artistic interests is consistent with an evolved folk psychology. Individuals with artistic interests score highly on measures of verbal and perceptual abilities and highly on the personality dimension of openness, and along with individuals with social and enterprising interests often have relatively poor mechanical abilities, consistent with niche specialization (Ackerman & Heggestad, 1997; Randahl, 1991). Although people with social and enterprising interests tend to be high on the extraversion dimension of personality (Larson et al., 2002), there are some data inconsistent with the prediction that enhanced social interests should correspond with enhanced folk psychological abilities. Ackerman and Heggestad found that verbal abilities, as measured by psychometric tests, were unrelated to social interests and inversely related to enterprising interests.

However, examination of Figure 1.2 reveals that the predicted folk psychological abilities do not map onto verbal psychometric tests, with the exception of language (Carroll, 1993). Even language as used in a natural context to develop social relationships and to influence the behavior of other people is functionally different in many ways than the competencies measured by verbal tests. Moreover, Randahl (1991) found intraindividual variation in abilities across occupational interests. People with strong social and enterprising interests appear to have lower *g* scores, at least in this college sample ( $n = 846$ ), than people with strong realistic, investigative, and artistic interests, and thus their verbal scores relative to other people are not elevated. However, people with social and enterprising interests are better verbally than they are quantitatively or spatially and thus their social interests (i.e., extraversion) allow them to capitalize on an intraindividual strength.

In any case, testable predictions that follow from my proposal are that individual differences in social, enterprising, and artistic interests should be related to performance differences on measures that capture sensitivity to the meaning of nonverbal behavior and facial expressions, competencies on theory of mind tests, and so forth. A more specific prediction is that individuals with social interests may excel at the individual-level competencies shown in Figure 1.2, and individuals with enterprising interests may excel at the group-level competencies associated with organizing and focusing the behavior of members of their in-group. These interest-ability relations are expected to emerge epigenetically (Bouchard et al., 1996; Scarr, 1993); that is, through interactions between inherent biases to engage in niche-related behaviors (e.g., seeking social relationships and



social information), and inherent but nascent attentional and cognitive advantages (e.g., sensitivity to facial expressions). The combination results in practice of the supporting cognitive competencies and their enhancement during development.

The concrete/abstract dimension does not map directly onto the folk domains shown in Figure 1.2, but is consistent with the conscious psychological mechanism of the motivation to control model, that is, the ability to mentally represent and manipulate past, present, or potential future states. These representations would be toward the abstract pole of the concrete/abstract dimension. Use of symbols and other forms of abstract expression are ubiquitous across human societies and are manifested in terms of music, dance, art, poetry, and story telling. These activities express the experiences of the in-group and often serve to increase social cohesion and cooperation (Alcorta & Sosis, 2005; Brown, 1991; Coe, Aiken, & Palmer, 2006). Abstractions are also found in explanations of social (e.g., illness due to witchcraft) and natural (e.g., storms) phenomena that are not well understood by individuals in the culture (Brown, 1991). The latter are commonly expressed in terms of mystical explanations (e.g., gods, witchcraft) and are often accompanied by rituals designed to attempt to control these phenomena (e.g., to cure sickness). Although these folk explanations are not typically scientifically accurate, as Newton railed (1995), they may provide a sense of psychological control and perhaps a means of developing methods of actual utility (e.g., folk medicine) and cross-generational transmission (e.g., stories). More mundane rituals—building fires, gathering food, and so on—are also a universal and necessary feature of day-to-day living in human cultures, and cluster toward the concrete pole of the concrete/abstract dimension.

There are several lines of evidence that support the prediction of inherent and potentially evolved influences on individual differences on the people/things and concrete/abstract dimensions of interest, and thus occupational niche seeking. As with basic dimensions of personality (e.g., extraversion, openness to experience), individual differences in occupational preferences and underlying interests (e.g., in nature) are moderately heritable (Betsworth et al., 1994; Lykken, Bouchard, McGue, & Tellegen, 1993). Sex differences in orientation toward things (males) or interpersonal relationships (females) are predicted from evolutionary theory, as described elsewhere (Geary, 1998, 2002b), and these in turn are related to sex differences in occupational sorting in modern society (e.g., K. R. Browne, 2005; Geary, *in press*; Lubinski, 2000). As an example, activities performed exclusively or primarily by men in traditional societies include metal working, weapon making, and working with wood, stone, bone and shells, among other activities (Daly & Wilson, 1983; Murdock, 1981). Across cultures, nearly 92% of those activities that appear to

be most similar to the likely tool-making activities of *Homo habilis* and *H. erectus* (i.e., use of wood, stone, bone, and shells) are performed exclusively by men (Gowlett, 1992).

A sex difference, favoring boys and men, is thus predicted and found for interest in working with objects and in corresponding mechanical abilities (Geary, 1998; Hedges & Nowell, 1995). These, in turn, appear to emerge during development through an interaction between the influence of male hormones on activity biases and cognition (Cohen-Bendahan, van de Beek, & Berenbaum, 2005) and object-oriented play and exploration (Gredlein & Bjorklund, 2005). In adulthood, this is expressed in modern societies as a sex difference, favoring men, in realistic interests and work in associated occupations (K. R. Browne, 2005).

***Evolved Interests and Children's Development.*** If social competition was a potent selection pressure during recent human evolutionary history (Alexander, 1989; Geary, 2005; Flinn et al., 2005), then a significant proportion of children's self-directed activities is predicted to be social and to create evolutionarily expectant experiences that flesh out the folk psychological competencies shown in Figure 1.2. Many children are also predicted to engage in activities that will flesh out folk biological and folk physical competencies. Examples of the latter include object-oriented play and exploration of the physical environment (folk physics), as well as the collection and perhaps play hunting of other species (folk biology); Darwin, for instance, was an avid beetle collector in his adolescence (J. Browne, 1995). Indeed, studies of infants' attentional biases and preschool children's nascent and implicit knowledge are often focused on the domains of folk psychology, folk biology, and folk physics (e.g., S. A. Gelman, 2003; Keil, 1992; Keil, Levin, Richman, & Gutheil, 1999; Mandler, 1992; Wellman & Gelman, 1992), although these have not been well linked with observational studies of children's and adolescents' self-directed activities (for discussion see Geary et al., 2003), and the source (inherent bias vs. experience) of these emerging competencies is debated (Au & Romo, 1999). My point is that there is theoretical and empirical research on children's early attentional biases and activity preferences that must be considered in attempts to understand how children's presumably natural preferences are expressed in school settings and how these might relate to later interest biases in other important evolutionarily novel contexts, including the workplace.

Any continuity between children's evolved interests and activities preferences and Holland's (1996) RIASEC model would in theory emerge from the underlying people/things, concrete/abstract dimensions shown in Figure 1.5. Individual variation in specific occupational interests (e.g., physicist vs. lawyer) are predicted to emerge only as children are exposed to opportunities to express their more basic interests within the wider cul-

ture (Lykken et al., 1993). In this view, basic interest dimensions (e.g., people/things) are to Holland's occupational taxonomy, as primary folk abilities are to secondary school-taught abilities; the latter is dependent on the former, but the specifics of the latter are also dependent on developmental experiences within a cultural context. In an attempt to directly assess the relation between children's activity preferences and Holland's occupational RIASEC hexagon, Tracey and Ward (1998) developed the *Inventory of Children's Activities* (ICA). The items were developed based on observation of children's activities, and activities that, in theory, capture later occupational interests and the underlying people/things, concrete/abstract (i.e., data/ideas) dimensions. Across two studies, the ICA was administered to elementary school (4th & 5th grade), middle school (6th–8th grade), and college students. The basic RIASEC pattern and the people/things, concrete/abstract dimensions emerged for the college sample, as expected.

For the elementary school sample and for girls and boys respectively, a sex-typed people/things dimension emerged but the abstract/concrete dimension did not. Rather, children's activities varied along an out-of-school (e.g., talking to friends) and in-school (e.g., adding numbers) dimension. The pattern for the middle school students was intermediate between that of the college students and the elementary students. In keeping with the elementary school findings, individual differences in children's self-directed activities along the people/things dimension are found during the preschool years (Golombok & Rust, 1993; Jennings, 1975), and possibly in infancy (Lutchmaya & Baron-Cohen, 2002). These and later individual differences tend to be highly sex-typed (Golombok & Rust, 1993; Tracey & Ward, 1998), but in ways consistent with evolutionary theory (Geary, 1998). As mentioned earlier, men's interest in objects and a corresponding enhancement of mechanical and spatial abilities follow from a likely evolutionary history of greater tool use in our male than in our female ancestors and is preceded by a sex difference in object/tool-related activities and play (Chen & Siegler, 2000; Gredlein & Bjorklund, 2005).

The failure to find to a concrete/abstract dimension in the elementary school samples may indicate that individual variation along this interest dimension emerges later in development than does variation across the people/things dimension. It is certainly the case that children engage in symbolic representation of their experiences, as in sociodramatic play, and use these activities to rehearse commonly observed adult activities (e.g., playing house), many of which would be considered conventional in the RIASEC. In any event, the overall pattern reveals a potential continuity between children's and adolescents' interest and activities biases—the basic people/things dimension and perhaps the concrete/abstract dimen-

sion—and interest patterns that emerges across modern occupations. The bottom line is there may be a deep structure to children's and adults' interests that can be organized around folk psychology (interest in people), folk biology (interest in living things), and folk physics (interest in inanimate things). This deep structure also involves use of conscious psychological and working memory systems to create symbolic representations of experiences and a means (e.g., story telling) of conveying these experiences and other forms of knowledge across time and space. The content of these representations is predicted to coalesce around the folk domains and serve social functions (e.g., group cohesion) and utilitarian functions related to the acquisition and control of ecological resources (e.g., hunting strategy or tool construction).

### ***Motivation in School***

***Evolutionary Biases.*** The gist of the above argument is that children's natural motivational biases and conative preferences are focused on learning about themselves and other people (folk psychology), other living beings (folk biology), and the physical environment (folk physics). And, that they prefer to engage in this learning through a combination of physical activity (e.g., imitation of hunting) and symbolic representation (i.e., along the concrete/abstract dimension). Children may or may not be explicitly aware of these biases (e.g., as assessed in a survey) but they are nonetheless inferable through children's self-directed activities. Either way, this perspective provides a means of interpreting the finding that many school children value achievement in sports more than achievement in core academic areas (Eccles et al., 1993), and report that in-school activities are a significant source of negative affect (R. Larson & Asmusen, 1991). For a nationally (U.S.) representative sample, Csikszentmihalyi and Hunter (2003) found that the lowest levels of happiness were experienced by children and adolescents while they were doing homework, listening to lectures, and doing mathematics, whereas highest levels were experienced when they were talking with friends. For high-school students, the weekend is the highlight of their week, largely because they can socialize with their peers (R. Larson & Richards, 1998).

A preference for engagement in peer relationships is a predicted aspect of development for all highly social species (e.g., Joffe, 1997). The finding for sports is not surprising because these games involve ritualized practice of organized in-group/out-group competition and readily maps onto the learning of group-level folk psychological competencies, especially for boys (Geary et al., 2003). The lower valuation of achievement in formal academic areas, such as mathematics and reading (Eccles et al., 1993), and preference for out-of-school social activities (Csikszentmihalyi & Larson, 1987) can be framed in terms of the rapid accumulation of bio-

logically secondary knowledge illustrated in the section titled Human Intellectual History and the Creature of Culture, and the widening gap between this knowledge and people's inherent folk abilities and corresponding motivational and conative biases. The constellation of interest, ability, and motivational traits of the creative-productive individuals who generate this secondary knowledge is rare (Murray, 2003; Simonton, 1999a), and thus it cannot be expected that most children, or even many children, will be motivated or able to easily recreate this knowledge in school settings without formal instruction; intellectually talented youth appear to be an exception (Bleske-Rechek, Lubinski, & Benbow, 2004), as described in the section titled Individual Differences in Secondary Learning.

Indeed, schools are an evolutionarily novel context in which the cross-generational transmission of secondary abilities (e.g., writing) and knowledge (e.g., that a right angle = 90°) is formalized (see the Principles section in Table 1.1). The formalization of schooling is not, however, completely foreign to our evolved learning and motivational biases, because the extended length of childhood and adolescence likely co-evolved with an interest in and ability to transfer culturally important information across generations, as noted earlier (Boyd & Richerson, 2005; Flinn, 1997; Henrich & McElreath, 2003). In other words, a species-typical curiosity about—potentially related to the “openness to experience” dimension of personality (e.g., Komarraju & Karau, 2005)—and an ability to learn evolutionarily novel information is predicted, as are substantive individual differences within the species-typical range. Nonetheless, the rapid cultural accumulation of secondary knowledge over the past several millennia has created a gap between evolved modes of inter-generational knowledge transfer and learning (e.g., story telling, apprenticeships) and between the motivation to engage in the corresponding activities and the forms of activity needed for secondary learning in modern society. If this were not the case, then the activities that produce creative-productive advancements, as illustrated by the processes that contributed to Darwin and Wallace's discovery of natural selection, would be mundane and readily duplicated outside of school. As Pinker (1994) has argued, language is an extraordinary ability that is unique to humans, but its acquisition is mundane and effortless for most children. But, this is not the case for Newtonian physics, classic geometry, and so forth.

***Achievement Motivation.*** A complete review and integration of the extensive and nuanced literature on children's achievement motivation and related constructs (Ames & Archer, 1988; Barron & Harackiewicz, 2001; Dweck & Leggett, 1988; Eccles et al., 1993; Eccles, Wigfield, & Schiefele, 1998; Grant & Dweck, 2003; Meece, Anderman, & Anderman,

← Au: Should  
Boyd &  
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2006; Nicholls, 1984; Weiner, 1985, 1990; Wigfield & Eccles, 2000), as these potentially relate to my evolutionary framework, is beyond the scope of this chapter. These models of achievement motivation include children's understanding of the relation between effort and ability on academic outcomes (Nicholls, 1984); valuation of academic learning in terms of mastery (i.e., intrinsically motivated desire for a deep understanding of the material) or performance (e.g., focus on grades, standing relative to others) goals (Ames & Archer, 1988; Dweck & Leggett, 1988; Grant & Dweck, 2003); academic self efficacy (e.g., Bandura, 1993); and, expectancy of success and attributions regarding the sources of success or failure (e.g. ability vs. bad luck) in achieving academic goals (Eccles et al., 1998; Weiner, 1985; Wigfield & Eccles, 2000).

← Au: Wiener spelling did not match spelling in refs. It was changed to match ref spelling

The perceived value of achievement in one domain or another is also important and this, in turn, is influenced by intrinsic interests and by extrinsic utility; the latter is the usefulness of the academic knowledge for later goals, such as college entrance or employment (Wigfield & Eccles, 2000). Empirical studies indicate that expectancies, values, and so forth become increasingly differentiated across academic domains with schooling (Bong, 2001; Smith & Fouad, 1999), and that variables representing many of these constructs predict academic achievement above and beyond the influence of *gF* and various demographic factors (e.g., Duckworth & Seligman, 2005; Gagné & St Père, 2003; Lent, Brown, & Hackett, 1994).

One point of connection between my motivation-to-control model and models of academic motivation is Bandura's (1997) highly influential theory of social and cognitive self efficacy: "People make causal contributions to their own functioning through mechanisms of personal agency. Among the mechanisms of agency, none is more central or pervasive than people's beliefs about their capabilities to exercise control over their own level of functioning and over events that affect their lives" (Bandura, 1993, p. 118). Self efficacy is an aspect of this personal agency and at its core is a self-referenced appraisal regarding the likelihood of success in various domains and through this influences, among other things, the pursuit of achievement in these domains and persistence in the face of failure. Bandura emphasizes one's explicit appraisal of efficacy and attributions regarding associated outcomes (e.g., cause of failure), and these in turn map onto the folk psychological domains of self awareness, self schema, and the ability to explicitly represent associated information in the conscious psychological component of control-related mental models. The content of mental models will include attributional biases, expectancies, and other social learning mechanisms that can influence evaluations of future goals and behavioral persistence in attempts to achieve these goals (Geary, 2005).

In other words, Bandura's (1993, 1997) model of self-efficacy is highly consistent with an evolutionary perspective, but with different points of emphasis regarding children's academic motivations and corresponding self evaluations. One area in which my evolutionary model differs from social learning theory is with my assumption of domain-specific and inherent learning and motivational biases associated with folk knowledge (Figure 1.2), but not academic knowledge, such as mathematics. Further, the core of the self schema is predicted, from an evolutionary perspective, to be referenced in terms of one's standing vis-à-vis peers and particularly for traits that have an evolutionary history, including physical abilities (greater importance for boys than girls), physical attractiveness (greater importance for girls than boys), social influence, and family status (Geary, 1998). These are predicted to be universal and implicit influences on the development of self schemas and self evaluations, whereas culturally specific activities, such as schooling, are predicted to be important in these cultures but less central to most children's and adolescents' emerging self schemas and evaluations. In keeping with this view is the finding that self awareness and the emerging self schema are embedded in a web of social relationships and that the best predictor of global self esteem from childhood to adulthood is perceived physical attractiveness (Harter, 1998) and not, for instances, grades in high school mathematics classes.

From an evolutionary perspective, the valuation of academic achievement and the relation between achievement and self-esteem is predicted to be highly variable across and within cultures, and to be heavily dependent on explicit parental and cultural valuation of associated activities and outcomes (e.g., grades; Stevenson & Stigler, 1992), and heavily influenced by peers' valuation of academic achievement (Harris, 1995). From a social learning perspective (Bandura, 1986), many children will imitate parents and teachers who engage in academic activities (e.g., reading); many will come to focus on these activities because they provide access to culturally valuable resources, such as a job and income; and, many will come to enjoy these activities in their own right, developing a mastery orientation (Winner, 2000). Children and adolescents will also develop a sense of academic self efficacy. These outcomes also follow from an evolutionary perspective that includes evolved modes of cross-generational knowledge transmission. The crucial difference comparing these theoretical views is with respect to specificity of predictions: With successive grade levels, academic content will increasingly diverge from its evolved foundation, as was illustrated in the section titled Primary and Secondary Forms of Cognition, and thus academic learning is predicted to become more difficult and any motivation to engage in this learning is predicted to decrease, and this is the case (Eccles et al., 1993). Social living also becomes more complex and nuanced as people mature into adulthood,

but motivational disengagement from social life is predicted to be far less common than disengagement from academic life.

Thus, if the goal is to educate nearly all children and adolescents in academic domains that are of a recent cultural origin and remote from folk domains, then there may be a need to *explicitly* highlight the utility of these skills in the culture and perhaps focus on the intellectual and academic accomplishments of creative-productive individuals, that is, show that these individuals are socially valued (Stevenson & Stigler, 1992). In other words, children's and adolescent's explicit valuation of academic learning, the perceived utility of academic skills, and the centrality of self efficacy in these areas to their overall self esteem are predicted to be highly dependent on sociocultural valuation of academic competencies, such as explicit rewards for academic achievement (e.g., honor rolls) and valuation of cultural innovators (e.g., Edison). In contrast, the children's and adolescent's valuation of and perceived efficacy related to their physical traits or social relationships are an implicit features of their evolved folk psychology, contrary to current assumptions regarding the source of the focus on these traits (e.g. Harter, 1998).

### **Biologically Secondary Learning**

Biologically secondary learning is the acquisition of culturally important information and skills (gC-secondary) by means of the evolved mechanisms, including gF, that enable people to cope with novelty and change and that enable the cross-generational transfer of cultural knowledge. Evidence for the importance of gF for learning in novel contexts, such as school and the workplace, is well known and documented (L. Gottfredson, 1997; Jensen, 1998; Walberg, 1984). In contrast, the importance of specific abilities for success in school or at work is often hypothesized (Gardner, 1983; Kalbleisch, 2004; Sternberg, 2000; Winner, 2000), as it is here (see below), but the empirical evidence for their importance, above and beyond the influence of gF, has been found for only a few academic domains and occupations (Baron-Cohen et al., 1999; Humphreys, Lubinski, & Yao, 1993; Shea, Lubinski, & Benbow, 2001). In the first section, I attempt to elaborate on the mechanisms underlying the relation between gF and the ability to acquire evolutionarily novel competencies, and in the second I discuss ways in which gF and specific folk abilities might interact in the acquisition of biologically secondary abilities and knowledge. In the final section, I discuss individual differences in secondary learning and accompanying educational implications.



### ***Fluid Intelligence and Secondary Learning***

The correlation between performance on measures of *gF* and ease of learning in evolutionarily novel contexts does not inform us as to how fluid intelligence actually affects the learning process. In the following sections, I review research on the mechanisms that appear to relate *gF* to secondary learning, and discuss applied examples in Folk Systems and Secondary Learning.

***Inhibition of Folk Biases.*** One of the principles of evolutionary educational psychology (see Table 1.1) states that children are biased to engage in activities that will adapt folk knowledge to local conditions, and these biases will often conflict with the need to engage in the activities needed for secondary learning. The principle follows from the rapid (and accelerating) cross-generational accumulation of secondary knowledge over the past several millennia. One implication is that evolved folk attributional (e.g., the folk physical concept of “impetus,” as I described earlier) and behavioral (e.g., preference for peer activities over mathematics homework) biases will often need to be inhibited before secondary learning will occur. Indeed, educational research supports the importance of inhibitory control for school-based learning (Duckworth & Seligman, 2005; Fabes, Martin, Hanish, Anders, & Madden-Derdich, 2003) and is consistent with empirical research on the cognitive components of *gF*; specifically, attentional focus and an ability to inhibit irrelevant information from entering working memory (Engle, 2002; Engle et al., 1999; Kane & Engle, 2002).

Engagement of these inhibitory mechanisms is predicted to be effortful and to occur in evolutionarily novel contexts and for information the individual explicitly determines to be useful in terms of meeting control-related goals. In the case of schooling and culturally evolving secondary knowledge, however, it cannot be expected that children will understand which forms of secondary knowledge will be necessary for successful living as an adult. For that matter, in cultures with rapid changes in secondary knowledge, educators cannot fully know what is necessary for their students’ long-term employment and cultural needs. Even in these cultures there are core skills (e.g., reading) that must be taught and learned, and it is adults, not children, who must determine these core skills and what is culturally-important knowledge.

***Process of Secondary Learning.*** Ackerman (1988) proposed the mechanisms that relate *gF* to learning can be divided into three stages, cognitive, perceptual-speed, and psychomotor (see also Anderson, 1982). The gist is that different abilities are related to individual differences in academic and job-related performance at different points in the learning process. For school-based and job-related learning, the cognitive stage refers to the relation between *gF* and initial task performance. The prediction is that novel and complex tasks will require an attention-driven,

explicit representation of task goals and information patterns in working memory. During this phase, the task goals and the sequence of steps needed to perform the task are learned, and memorized. With enough practice, the eventual result is the automatic, implicit processing of task features and automatic behavioral responses to these features. These phases of learning represent the shift from explicit representations and controlled problem solving to automatic, implicit and heuristic-based processing of and responding to the task, as illustrated by the arrow in the center of Figure 1.3. Ackerman's model can be readily integrated with the folk systems shown in Figure 1.2, if we assume that one core difference between biologically primary competencies and biologically secondary competencies is the need for the cognitive phase of learning. The inherent constraints associated with evolved competencies can be understood as putting them at Ackerman's second or third phase of learning—resulting in their implicit operation—without the need for the explicit learning associated with this first phase.

A work-related example is provided by tasks that simulate the demands of an air traffic controller, which is clearly an evolutionarily novel demand. One task involves learning the rules that govern decision making, such as whether to keep a plane in a holding pattern or allow it to land based on air traffic, wind, and so forth. Another task involves the especially complex demands of tracking and making decisions based on constantly changing information patterns (e.g., multiple plane icons) represented on dynamic radar screens (Ackerman & Cianciolo, 2000, 2002). Performance on these tasks is indexed by the number of properly routed flights and speed of making routing decisions. Ease of initial rule learning is moderately correlated with  $gF$  ( $r_s \sim 0.4$  to  $0.5$ ), and remains so even after six hours of practice ( $r \sim 0.3$ ). Performance on the radar task is moderately to highly correlated with  $gF$  ( $r_s \sim 0.4$  to  $0.8$ ), and remains so throughout training. A causal relation between performance and  $gF$  was experimentally demonstrated by manipulating the number of planes the individual needed to simultaneously monitor. As the number of planes increased, the importance of  $gF$  increased.

**Cognitive and Brain Mechanisms.** On the basis of work described in the section titled Evolution of General Intelligence, the initial learning of evolutionarily novel academic and job-related competencies, as illustrated by Ackerman's (1988) research, is driven by the ability to control attention, inhibit irrelevant information (both  $gC$ -primary and  $gC$ -secondary), simultaneously represent multiple pieces of information in working memory, and logically piece this information together to meet problem-solving goals (e.g., Embretson, 1995; Fry & Hale, 2000; Kane & Engle, 2002). In many cases, the drawing of inferences about information represented in working memory will be facilitated if the information is made available to

conscious awareness, although pattern learning can occur without awareness (Stadler & Frensch, 1997). For explicit learning and problem solving, the supporting brain regions appear to be the dorsolateral prefrontal cortex (areas 47, 9 in both panels of Figure 1.4), the anterior cingulate cortex (area 24 in the lower panel), and the posterior attentional systems of the parietal cortex (area 40 in the upper panel; e.g., Duncan, 2001; Duncan & Owen, 2000). Other areas are also active when people are engaged in these tasks, and there are, of course, different patterns of brain activity associated with learning one type of skill or another (e.g., McCandliss, Posner, & Givón, 1997). Additional research is needed, but current evidence suggests the dorsolateral prefrontal cortex and anterior cingulate cortex are primarily engaged during Ackerman's (1988) first phase of learning (Raichle, Fiez, Videen, MacLeod, Pardo, & Petersen, 1994). Thereafter, brain activation is associated with the particular type of stimulus (e.g., visual vs. auditory) and the specifics of task demands.

There are only a few studies that have combined learning and brain imaging with assessments of *gF* (e.g., Gevins & Smith, 2000; Haier, Siegel, Tang, Abel, & Buchsbaum, 1992). Haier et al. assessed the brain's use of glucose during the learning of a novel spatial problem-solving task. Individuals with high IQ scores learned the task more quickly than their less-intelligent peers, and showed more rapid declines in glucose metabolism across learning trials. Using electrophysiological methods, Gevins and Smith found the dorsolateral prefrontal cortex was initially engaged during the learning of a complex task that required working memory and attentional control, but engagement of this region declined as individuals learned the task. The decline was especially pronounced for intelligent individuals, who in turn appeared to shift the processing of task requirements to more posterior regions of the brain.

At this point, it appears that one function of the dorsolateral prefrontal cortex, the anterior cingulate cortex, and the posterior attentional system is to ensure the synchronized activity of other brain regions, such that anatomical and functional links are formed among these regions; see the description in the section titled Neuroscience Research. When couched in terms of *gF*, it appears that the associated ability to focus attentional resources and inhibit the activation of task-irrelevant information (Kane & Engle, 2002) results in the ability to synchronize only those brain regions needed for secondary learning. The result would be lower glucose use and faster learning for individuals high in *gF*, because fewer unneeded brain regions are activated and thus fewer regions are anatomically linked. Functionally, the result would be a sharper representation and better understanding of the new competency, because irrelevant information and concepts would not be linked to this competency. Once formed, an evolutionarily novel, biologically secondary cognitive compe-

tency emerges. The more fundamental issue concerns *how* these components of *gF* and supporting brain systems create competencies that do not have an evolutionary history.

### ***Folk Systems and Secondary Learning***

The attentional and working memory components of *gF* are engaged during the initial phase of biologically secondary learning, but the fully developed secondary competencies reside in a network of cognitive and brain systems that differ from those that support *gF* (Gevins & Smith, 2000; Raichle et al., 1994). These networks represent the two earlier noted classes of crystallized intelligence (Cattell, 1963), that is, *gC*-primary and *gC*-secondary. In effect, the components of *gF* are used to modify plastic *gC*-primary abilities to create *gC*-secondary abilities. As described in the section Cognitive Development and Modular Plasticity, there is evidence for plasticity in many primary modules, as well as an evolutionary logic as to why such plasticity is expected. However, limits on the plasticity of *gC*-primary modules implies these systems can be modified to create secondary competencies only to the extent this novel information is similar to the forms of information the system evolved to process (Sperber, 1994), and to the extent independent modular systems can be interconnected to form unique neural networks and functional competencies (Garlick, 2002; Sporns et al., 2000). In the first section, I discuss how the transformation from *gC*-primary to *gC*-secondary might occur in the domain of reading, and in the second I focus on the more complex domain of scientific reasoning.

### ***Folk Psychology and Reading***

As noted in the section Human Intellectual History and the Creation of Culture, I assume there are functional, motivational, cognitive, and neural links between secondary abilities and the primary folk systems from which they are built, although the “remoteness” of many of these links increases with the cross-generational accumulation of secondary knowledge and across school grade levels (Geary, 2002a). If this assumption is correct, then empirical links between basic secondary abilities and knowledge—those that tend to be taught in the early years of schooling—and one or several of the primary domains shown in Figure 1.2 should be found. The most crucial mechanisms of cross-generational knowledge transfer in modern societies, that is, reading and writing, are included among these secondary abilities. In terms of cultural history, these systems must have initially emerged from the motivational disposition to communicate with and influence the behavior of other people (e.g., morals in the Bible), and are predicted to engage at least some of the social communication systems shown in Figure 1.2, that is, components of folk

psychology. In fact, it has been suggested many times that reading is built on evolved language systems (e.g., Mann, 1984; Rozin, 1976). My goal here is describe the basic relations between language processing and processing in other folk psychological domains and reading, and by doing so provide directions as to how this form of analysis might be used more generally with an evolutionary educational psychology.

**Cognitive Mechanisms.** Research on the cognitive predictors of children's reading acquisition, the effectiveness of various types of reading instruction, and sources of individual differences in ease of learning to read provide solid support for the prediction that the core components of reading competency are dependent on primary language skills (Bradley & Bryant, 1983; Connor, Morrison, & Petrella, 2004; Hindson, Byrne, Shankweiler, Fielding-Barnsley, Newman, & Hine, 2005; Lovett, Lacerenza, Borden, Frijters, Steinbach, & De Palma, 2000; Mann, 1984; Moats & Foorman, 1997; Stevens, Slavin, & Farnish, 1991; Vukovic & Siegel, 2006; Wagner & Torgesen, 1987; Wagner, Torgesen, & Rashotte, 1994). The crucial components in early reading acquisition include an explicit awareness of distinct language sounds, that is, phonemic awareness, and the ability to decode unfamiliar written words into these basic sounds. Decoding requires an *explicit* representation of the sound (e.g., *ba*, *da*, *ka*) in phonemic working memory and the association of this sound, as well as blends of sounds, with corresponding visual patterns, specifically letters (e.g., *b*, *d*, *k*) and letter combinations (Bradley & Bryant, 1983). Phonetic working memory has also been proposed as the mechanism that supports vocabulary acquisition during natural language learning (Baddeley et al., 1998; Mann, 1984), but this form of word learning occurs quickly (some-time with one exposure) and the associated mechanisms operate *implicitly* (Lenneberg, 1969; Pinker, 1994).

Wagner et al. (1994) found individual differences in the fidelity of kindergarten children's phonological processing systems to be strongly predictive of the ease with which basic word decoding skills are acquired in first grade. Children who show a strong explicit awareness of basic language sounds are more skilled than are other children at associating these sounds with the symbol system of the written language. The majority of children acquire these competencies most effectively with systematic, organized, and teacher-directed explicit instruction on phoneme identification, blending, and word decoding (e.g., Connor et al., 2004; Hindson et al., 2005; Lovett et al., 2000; Stevens et al., 1991). Other components of skilled reading include fluency and text comprehension. Fluency is the fast and automatic retrieval of word meanings as they are read, which is related in part to frequency with which the word has been encountered or practiced in the past (e.g., Sereno & Rayner, 2003). Text comprehension involves coming to understand the meaning of the composition and

involves a number of component skills, such as locating main themes and distinguishing highly relevant from less relevant passages. Unlike comprehension of spoken language (Pinker, 1994), explicit instruction in the use of these strategies for understanding written text is needed for many children (Connor et al., 2004; Stevens et al., 1991).

**Brain Mechanisms.** The neuroanatomy of basic language abilities has been understood for more than 100 years (e.g., Martin, 2005; Poldrack, Wagner, Prull, Desmond, Glover, & Gabrieli, 1999; Price, 2000), and has substantive overlap with the brain regions that support the acquisition of basic phonological decoding, reading fluency, and text comprehension (Paulesu et al., 2001; Price & Mechelli, 2005; Pugh et al., 1997; Temple, 2002; Turkeltaub, Eden, Jones, & Zeffiro, 2002; Turkeltaub, Gareau, Flowers, Zeffiro, & Eden, 2003). In a thorough review of neuropsychological and brain imaging research on language processing, Price (2000) concluded (and I have simplified here) that passive processing of language sounds occurs in the traditional Wernicke's area (posterior region of area 22 in the upper panel of Figure 1.4); speech production involves Broca's area (area 44 in the lower panel) and areas that support word articulation (e.g., area 6 in both panels); and, the representations of the meaning of spoken and heard utterances is distributed across the temporal (e.g., areas 21, 38 in both panels), and parietal (areas 39, 40 in the upper panel) cortices. Prefrontal working memory areas related to language (areas 45, 47 in the upper panel) are engaged when the speaker or listener has to make active decisions about the utterances (Poldrack et al., 1999). Although there is a left-hemispheric bias for much of this processing, the corresponding regions in the right-hemisphere are often engaged as well.

Brain imaging studies of individuals with normal reading acquisition and those with reading disability are beginning to provide insights into the areas of convergence and divergence comparing reading and natural language processing, and the brain regions that support core reading abilities. Among other regions, tasks that tap phonological awareness or involve phonological decoding engage Wernicke's and Broca's areas (Paulesu et al., 2001; Turkeltaub et al., 2003), as do tasks that involve the reading of single words (Pugh et al., 1997; Turkeltaub et al., 2002). Word reading also engages areas in the temporal (e.g., area 21 in the upper panel) and parietal (e.g., area 39 in the upper panel) cortices that support the comprehension of spoken utterances (Price & Mechelli, 2005). Early research on the comprehension of the syntax and the basic meaning of read sentences suggested engagement of the same brain regions that support the production and comprehension of spoken utterances, including Broca's and Wernicke's areas, although both hemispheres were involved in sentence reading (Just, Carpenter, Keller, Eddy, & Thulborn, 1996). Subsequent studies are generally consistent with this finding, but also sug-

gest involvement of additional regions of the temporal cortex (e.g., areas 38, 21) and part of the parietal cortex (area 39), areas also involved in language comprehension (Caplan, 2004; Price, 2000).

There are also important differences between language processing and reading. Areas at the junction of the temporal and occipital lobes (e.g., area 37) are more likely to be engaged during reading than during natural language processing. An intriguing exception might be natural object naming, which engages this same temporal/occipital area (Price & Mechelli, 2005). Basically, learning to read and skilled reading in adulthood involve the integration of the visual systems that process the orthography of written symbols and those that translate these images into the language-based sounds that support the comprehension and production (e.g., reading aloud) of the read material (Simos, Fletcher, Francis, Castillo, Patariaia, & Denton, 2005; Paulesu et al., 2001).

**Summary and Integration.** As noted, the argument that reading and reading acquisition are built on language systems is by no means novel (Mann, 1984; Rozin, 1976; for a related argument on writing see Karmiloff-Smith, 1992). However, I hope an evolutionarily informed analysis of the associated cognitive and brain links will provide a more nuanced understanding of the specific relation between reading/language and, more generally, an example of how this type of analysis can be used to better understand the learning of other secondary abilities. Text that is read aloud or silently engages the same network of brain regions and results in the same types of cognitive representations (i.e., language sounds) involved in generating or listening to natural language, in keeping with the prediction that there will be a close relation between secondary abilities and the primary systems from which they are built (Sperber, 1994). Moreover, this tight relation is in keeping with the view that the cultural construction and development of written symbols was to socially communicate; in other words, reading and writing may tap the same underlying motivational systems that are components of folk psychology, unlike secondary abilities (e.g., geometry) built on folk physical or folk biological systems.

For most children, learning how to phonemically decode words and to use text comprehension strategies is facilitated by explicit, teacher-organized instruction (Connor et al., 2004; Hindson et al., 2005). The necessity of teacher and curriculum organization of secondary material follows logically, if one assumes that much of this material has been generated in the past several generations or millennia of human history and that children therefore do not have built-in attentional, cognitive, or motivational mechanisms that will drive child-centered learning in these domains. The need for explicit instruction also follows from my proposal that the ability to generate and learn evolutionarily novel content and abilities, such as

written text and reading, are dependent on the systems that evolved to generate and cope with social and ecological conditions that tend to vary during the human life span (Geary, 2005). The mechanisms are associated with *gF*; specifically, the ability to inhibit primary heuristics and explicitly represent, through attentional control, variation in social or ecological conditions in working memory and then use problem solving to devise behavioral strategies to cope with these dynamics.

For instance, during the initial phases of reading acquisition, attentional focus on the relation between the sound and written letter (when decoding) or word (when reading) should, in theory, result in the amplification of the activity of the brain regions that process these auditory and visual forms of information, and their simultaneous representation in working memory. This may involve the integration of brain areas involved in object naming (e.g., area 37 in both panels in Figure 1.4) and those involved in phonetic (Wernicke's area) and semantic (e.g., areas 38, 39 in both panels) language processing (Price & Mechelli, 2005). The synchronization and integration of these normally distinct systems would initially involve the attentional and working memory systems of the dorsolateral prefrontal cortex (e.g., areas 9, 46 in the upper panel), but with sufficient practice the formation of a learned association between the sound and letter or word should occur. In this view, the reading of printed words involves integration of two biologically primary systems. The first supports the naming and description of visually processed objects in the real world and the second involves the access to concepts associated with these utterances. With extended practice, the association becomes represented in long-term memory and thus becomes implicit knowledge, representing Ackerman's (1988) final stages of learning. When this is achieved, the association between the sound and letter, or letter combination and word sound, is automatically triggered when the letter string is processed during the act of reading and thus no longer engages the prefrontal cortex and no longer requires *gF*. In keeping with this prediction, one potential source of reading disability is a poor white-matter connection between these object naming and phonetic/semantic brain regions, even for children with average or better IQ scores (Paulesu et al., 2001; Simos et al., 2005; Temple, 2002).

A more novel evolution-based prediction is that reading comprehension will also be dependent on theory of mind and other folk psychological domains, at least for literary stories, poems, dramas, and other genre that involve human relationships (Geary, 1998). Most of these stories involve the recreation of social relationships, more complex patterns of social dynamics, and even elaborate person schema knowledge for main characters. The theme of many of the most popular genre involves the dynamics of mating relationships (e.g., romance novels) and intrasexual



competition for over mates (e.g., Whissell, 1996), and often involves the social scenario building that Alexander (1989), myself (Geary, 2005), and others (e.g., Flinn et al., 2005; Humphrey, 1976) have argued is a competency that evolved as the result of intense social competition. In other words, once people learn to read, they engage in this secondary activity because it allows for the representation of more primary themes, particularly the mental representation and rehearsal of social dynamics. In addition to social relationships, the RIASEC model (Holland, 1996; Lubinski & Benbow, 2000) and the underlying people/things dimension of interests indicates that some people will be interested in reading about mechanical things (e.g., the magazine *Popular Mechanics*) and biological phenomena (e.g., the magazine *Natural History*). For instance, the content of children's literature also includes other living things, such as dinosaurs, and thus may capture an inherent interest in folk biology. These individual differences, as well as the more fundamental desire to exert some level of personal control, suggest that children should be given some choice in the literature they read, but only once basic skills are acquired.

### ***Evolution and Science Education***

The learning of phonemic decoding and other basic reading skills is a relatively simple task, but illustrates how the processes may work for the learning of more complex biologically secondary skills. The core difference across task complexity involves the length of the first phase of learning, to use Ackerman's (1988) model. More precisely, complexity is predicted to be related to the extent to which the task is evolutionarily novel (granted, a system for making this determination remains to be fully articulated); the amount of information that must be identified and processed to deal with task demands; and, the extent to which this information changes across time. As each of these features increases in complexity, there is an accompanying increase in the need for sustained attention, working memory, and the ability to reason and make inferences, that is, an increased reliance on *gF*. Scientific reasoning is one of the most complex tasks in modern societies today (L. Gottfredson, 1997) and—as illustrated by earlier discussion of Euclid (1956), Newton (1995), and Darwin (1859)—the results are among humanity's greatest accomplishments (Murray, 2003). Today, the scientific enterprise and the insights of individual scientists and teams of scientists are engines of cultural innovation, technological change, and generation of secondary knowledge. Yet, the ability to reason rationally and scientifically does not come naturally to most people (Stanovich, 1999; Stanovich & West, 2000), and in fact the scientific method is itself a cultural innovation and thus an understanding of this method is not expected to come easily to most people.

The literature on the cognitive mechanisms involved in scientific and mathematical reasoning and the use of experimentation to test naïve hypotheses includes the seminal studies by Piaget and his colleagues (e.g., Inhelder & Piaget, 1958; Piaget, Inhelder, Szeminska, 1960), and more recent studies that have approached these issues from an information-processing or neonativist (i.e., in terms of folk knowledge) perspective (e.g., Capon & Kuhn, 2004; Carey, 2001; Carey & Spelke, 1994; Chen & Klahr, 1999; Hunt & Minstrell, 1994; Klahr & Dunbar, 1988; Klahr & Nigam, 2004; Klahr & Simon, 1999; Koslowski, 1996; Kuhn, 1989, 2005; Kuhn & Dean, 2005; Shtulman, 2005; Williams, Papierno, Makel, & Ceci, 2004). An exhaustive review of this literature is not my goal and nor is it necessary, as excellent and recent reviews of this and related literatures are available elsewhere (Klahr, 2000; Klahr & Simon, 1999; Strauss, 1998; Zimmerman, 2000, 2005). Rather, in the first two respective sections, I highlight some of the research on the cognitive and brain mechanisms related to scientific reasoning and its development. In the final section, I discuss how these themes may potentially inform and be informed by an evolutionary educational psychology.

**Cognitive Mechanisms.** As described for Darwin and Wallace's (1858) discovery of natural selection, the achievement of scientific goals involves problem solving within an ill-defined problem space. The process is based on assumptions and prior knowledge that define the problem space, the use of experimentation and observation to generate and test hypotheses, and evaluation of experimental results related to these hypotheses. Similarly, the cognitive processes and knowledge bases around which naïve children's and adults' scientific reasoning and problem solving coalesce are the reciprocal interactions between theory-hypothesis generation, experimental testing, and evaluation of experimental results vis-à-vis generated hypotheses (Klahr & Dunbar, 1988; Klahr & Simon, 1999; Kuhn, 1989). Klahr and Dunbar's dual-space model of scientific reasoning has been particularly influential (see Zimmerman, 2000, 2005), as has the assumption that scientific reasoning and problem solving are developed from the same mechanisms (e.g., analogy, induction) used in everyday problem solving (Klahr & Simon, 1999). The dual spaces include an *hypothesis space*—the set of hypotheses related to the phenomena in question—derived from prior knowledge, assumptions, and observations, and an *experiment space*—the set of procedures available to generate or test hypotheses. The hypothesis space and associated knowledge bases will often differ across content domains, such as evolutionary biology and Newtonian physics, but aspects of the experiment space and the evaluation processes will be domain general (e.g., the empirical testing of hypotheses).

Wallace's (1855) conclusion that related species are found in the same geographic location because they all arose from a common ancestor that resided in this location was part of his hypothesis space and was related to his goal of discovering the natural law that resulted in the emergence of new species. Darwin, of course, had the same hypothesis, and spent many years explicitly testing this and related hypotheses. One example was the use of selective breeding (artificial selection) to produce different breeds of, for instance, pigeon (Darwin, 1859). The tests were drawn from his experiment space and the results were used to evaluate hypotheses about natural selection and potential refutations of these hypotheses (J. Browne, 1995). Darwin (and Wallace), nonetheless, made mistakes. Darwin's pangenesis theory of how traits were transmitted from parents to children was incorrect, but he resisted changing the theory even in the face of strong contradictory evidence (J. Browne, 2001). Even Newton spent many years engaged in unsuccessful alchemy experiments (White, 1998).

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And so it is with all people: As described in the section titled Cognitive Development and Modular Plasticity, children and adults have naïve folk beliefs about people, other living beings, and the physical world that provide a sense of coherence and control in their daily life, are often functional, and sometimes scientifically accurate (Wellman & Gelman, 1992). These folk beliefs and mental models of how the world works, however, are often scientifically inaccurate or incomplete. These misconceptions are nonetheless part of the a priori beliefs that influence children's and adult's scientific reasoning and their understanding of and ability to learn scientific concepts (Carey, 2001; Clement, 1982; Kuhn, 1989; McCloskey, 1983; Shtulman, 2006). In addition to priori and often incorrect beliefs, children and many naïve adults have difficulty separating the hypothesis and experiment spaces. There is a tendency to focus on observations and experimental results that confirm existing hypotheses (confirmation bias), and to ignore or discount disconfirming results. Many people view evidence as an example of an existing theory (and thus a confirmation), rather than viewing the theory "as an object of cognition, that is, [thinking] about the theory rather than with it" (Kuhn, 1989, p. 679).

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Kuhn's (1989) conclusion and that of others (Klahr & Dunbar, 1989; Klahr & Simon, 1999) suggests that the adaptation of everyday reasoning for use in scientific endeavors does not come easily. Indeed, the skilled use of everyday reasoning (e.g., analogy) in scientific contexts, separation of the hypothesis and experiment spaces, and acquiring appropriate rules of evidence for evaluating the relation between experimental results and hypotheses are highly dependent on formal instruction. At this time, there is no agreed upon instructional approach to bring about these ends. Research groups differ in the focus of their work (e.g., on the experiment space or hypothesis space) (Capon & Kuhn, 2004; Klahr & Nigam, 2004;

Williams et al., 2004), and often disagree on the most effective instructional methods (e.g., Klahr, 2005; Kuhn, 2005). Klahr and colleagues (Chen & Klahr, 1999; Klahr & Nigam, 2004), for instance, have demonstrated that explicit, teacher-directed instruction is more effective than child-directed discovery for learning how to control variables during experimental manipulations. Kuhn and Dean (2005) argued this approach may not promote effective transfer across domains and that conceptual learning may be more effectively achieved with a problem-based, discovery approach (e.g., Capon & Kuhn, 2002).

Although we await definitive results, in a very recent review of this literature Zimmerman (2005) concluded that some of the debate is definitional and perhaps less substantive than it appears; direct instruction often includes a “hands-on” component, and discovery is often guided (e.g., by prompts, questions) by teachers or experimenters. In any case, Zimmerman’s review indicates that an unguided self discovery approach is ineffective for teaching scientific reasoning to the vast majority of children before the fifth grade, and even for older individuals it is not sufficient; for instance, students often fail to develop experiments that would disconfirm their hypotheses. In short, most children and adults do not develop the full repertoire of skills related to the use of the scientific method without formal instruction that is extended over many years. Without solid instruction, children do not: (a) learn many basic scientific concepts, such as natural selection (Shtulman, 2006); (b) effectively separate and integrate the hypothesis and experiment spaces; (c) effectively generate experiments that include all manipulations needed to fully test and especially to disconfirm hypotheses; and (d) learn all of the rules of evidence for evaluating experimental results as these relate to hypothesis testing. In addition, they: (e) are often reluctant to give up naïve folk beliefs, even when faced with contradictory evidence (Zimmerman, 2005).

**Brain Mechanisms.** Brain imaging research on scientific reasoning and problem solving as related to science education is in its infancy and thus strong conclusions cannot yet be reached. Nonetheless, early studies and related research have provided intriguing insights into the potential brain systems that govern the inductive and deductive reasoning associated with scientific discovery and the processes involved in the generation and evaluation of hypotheses (Acuna, Eliassen, Donoghue, & Sanes, 2002; Dunbar & Fugelsang, 2005; Fugelsang & Dunbar, 2004; Goel & Dolan, 2000; Goel, Gold, Kapur, & Houle, 1998; Goel, Makale, & Grafman, 2004).

Fugelsang and Dunbar (2005) examined the brain regions involved in interpreting data that are either congruent or incongruent with a plausible or implausible mechanism governing the relation between use of psychotropic drugs and patient mood. There was more bilateral activation of

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the left- (areas 45, 47 in the upper panel of Figure 1.4) and right- (area 9 in both panels) prefrontal areas when adults evaluated data related to a plausible versus an implausible mechanism, suggesting that plausible mechanisms are more thoroughly evaluated. When participants evaluated data *inconsistent* with a plausible mechanism, there was even wider activation of the left dorsolateral prefrontal area (area 9 in both panels), as well as activation of the anterior cingulate cortex (areas 24, 32 in the lower panel). Dunbar, Fugelsang, and Stein (2006) examined the brain activity of naïve adults and physics students as they watched two videos on the motion of falling objects. The first video presented scientifically incorrect patterns of object motion consistent with naïve folk physical conceptions. The second video presented object motion consistent with Newtonian physics. When naïve adults watched the video of correct Newtonian motion, their dorsolateral prefrontal cortices were active, whereas only areas associated with memory were active for the physics students. The opposite pattern emerged for the video based on folk physical conceptions of motion.

The results suggest the cortical areas associated with attentional control, working memory, and conflict resolution are engaged only when presented with information inconsistent with current conceptual models of the phenomena; folk models for the naïve adults, and Newtonian models for the physics students. In keeping with this conclusion, Stavy, Goel, Critchley, and Dolan (2006) found that several areas of the occipital and parietal cortices (e.g., areas 18, 40 in both panels in Figure 1.4) are engaged when adults process intuitive, folk physical information associated with the area and perimeter of shapes. When judgments require access to formally taught geometric knowledge that conflicts with this folk knowledge, areas of the prefrontal cortex (e.g., 11, 47 in both panels) are engaged. For several of their participants, Dunbar et al. (2006) also found a disconnection between explicit statement of theory and brain activation; specifically, several naïve adults who explicitly stated the correct pattern of Newtonian motion showed brain activation patterns similar to that found with naïve adults who did not understand Newtonian motion. The results are consistent with cognitive models of concept development, namely that “deep” conceptual understanding and explicit statements of concepts are not the same thing (Kuhn, 1989).

In a series of related studies, Goel and colleagues have found that the systems of brain regions that support inductive and deductive reasoning differ and vary with whether the focus of reasoning involves familiar or unfamiliar information and easy or difficult judgments. Making difficult inductive inferences—generating an abstract rule based on examples and observations—engages several areas of the right prefrontal cortex (areas 47, 11 in both panels in Figure 1.4; Goel & Dolan, 2000). Drawing diffi-

cult deductive conclusions about familiar concepts—making a judgment about an outcome based on whether it logically follows from stated premises—often engages distributed areas within the left hemisphere; in particular: Broca’s area (area 45 in the upper panel), other prefrontal regions (e.g., areas 46, 47 in the upper panel), as well as several temporal areas (e.g., 22 in the upper panel) associated with concept representation (Goel et al., 1998). In contrast, deductive problems that involve unfamiliar geometric relations seem to be more dependent on the bilateral spatial-parietal systems than on the language systems (Goel et al., 2004).

The combination suggests that deductive problems involving familiar content are solved by means of attentional and working memory representations of preexisting concepts that tend to be explicitly cast in terms of language, whereas some deductive problems with unfamiliar geometric relations engage the bilateral visuospatial attentional and working memory systems. The solving of inductive problems also involves attentional control and working memory but is not dependent on language or access to preexisting concepts. The results for deductive problems are consistent with an explicit representation and manipulation of the processed information in working memory, but in these studies inductive tasks did not require explicit statement of the principles that bound together the presented examples and thus could have been solved implicitly. Of course, scientific discovery involves explicit statement of hypotheses and mechanisms, although implicit inductions may sometimes precede this: As stated earlier, Wallace’s statement that the mechanisms of natural selection “suddenly flashed upon me” (F. Darwin, 2000), was preceded by 13 years of observations and attempts to induce these mechanisms.

On the one hand, it is not surprising that scientific reasoning and evaluation of data engage areas of the prefrontal cortex associated with attentional control, working memory, and conflict resolution. On the other hand, there are several findings emerging from this literature that are important for science education and an emerging evolutionary educational psychology. It is important to know that different brain regions are involved in inductive and deductive reasoning; plausible mechanisms are evaluated more closely than implausible mechanisms; and data that conflict with predictions derived from plausible mechanisms are especially likely to trigger brain regions associated with cognitive conflict and working memory. The latter finding suggests that relevant aspects of the hypothesis space may need to be explicitly articulated and explicitly compared to relevant data derived from the experiment space for a thorough evaluation of concepts.

***Summary and Integration.*** From an evolutionary perspective, science emerged from recent cultural innovations that were driven by a small fraction of humanity (Murray, 2003), and therefore there is not a suite of bio-

logically primary cognitive systems or motivational biases to facilitate the teaching and learning of modern day science. As suggested in the section titled Human Intellectual History and the Creation of Culture, early scientists likely developed scientific concepts and experimental methods based on evolved cognitive and motivational systems associated with folk domains, but were able to inhibit these biases and use more general, if everyday, reasoning (e.g., analogy, induction) to construct increasingly accurate models of physical, biological, and social phenomena. These conceptual and methodological advances must be reconstructed for each and every generation, or they will be lost. The reconstruction is through science education. Science learning in modern societies requires, among other things that children come to understand (a) core concepts (e.g., natural selection, gravity) and experimental findings for many specific fields; (b) how scientists develop hypotheses from theory and observation and use experiments to test these hypotheses; (c) how to systematically develop their own experimental tests and to thoroughly relate experimental results to hypotheses; and (d) the rules of evidence for accepting and especially for disconfirming hypotheses (Klahr, 2000; Klahr & Dunbar, 1988; Kuhn 1989; Kuhn & Dean, 2005; Zimmerman, 2000, 2005).

From an evolutionary perspective, children are predicted to bring to the science classroom conceptual and attributional biases in the domains of folk psychology, folk biology, and folk physics (Wellman & Gelman, 1992). These constitute core aspects of their initial hypothesis space, which at times may facilitate the learning of associated scientific concepts and at other times will interfere with this learning (Kuhn, 1989; Zimmerman, 2005). One goal of an evolutionary educational psychology is to better integrate research on children's core knowledge and conceptual development in these domains (e.g., S. Gelman, 2003) into a coherent framework for guiding research on science education and learning in other academic domains. The integration will include knowledge about how and what children understand in these core domains and where this knowledge is consistent with or inconsistent with our scientific understanding of the same phenomena. As an example, on the basis of intense social competition, human folk psychological domains (see Figure 1.2) are predicted to be more fully articulated and biased than are folk biological or folk physical domains, and the associated biases are predicted to be self serving and function to guide attempts at behavioral control (Geary, 2005). A corresponding prediction is that more conceptual and attributional biases interfere with the scientific study and learning of social phenomena than of biological or physical phenomena, and this appears to be the case (Zimmerman, 2005). There are clear biases in folk biology and folk physics that influence learning in the biological and physical sciences, respectively, but biases in folk psychology may result in even

greater interference in learning the social sciences. Although people are inherently motivated to understand people and social relationships, this is not the same as understanding these phenomena scientifically. In fact, people are likely to be especially resistant to research results that “undermine” their sense of personal agency and control.

For an example of how folk knowledge might interfere with scientific learning in a key area of biology, consider Shtulman’s (2006) study of high school and college students’ conceptual understanding of natural selection. The students’ understanding was assessed in terms of their knowledge and integration of the basic mechanisms (e.g., within-species variation, inheritance) that result in natural selection. The same measures were administered to a contrast group of three evolutionary biologists. The latter, of course, understood each of the specific concepts (e.g., speciation) and had them integrated into a coherent mental model of the actual mechanisms of natural selection. Although the majority of high school and college students stated they were familiar with Darwin’s theory (76%), and agreed that natural selection was the best explanation of how species change over time (69%), the majority did not actually understand how natural selection works. They did, however, have a coherent theory of cross-generational change in species, albeit a theory that is not scientifically accurate. For instance, most of these individuals assumed that each species had its own essence that resulted in trivial within-species variation. Cross-generational change occurs at the level of the species’ essence and is driven by adaptive need, and not selection acting on heritable variation. Their knowledge seemed to be a mix of folk biology and misunderstood or poorly taught school biology.

In addition to misconceptions regarding species’ essence, there are several other ways in which such naïve folk biological concepts and biases might interfere with learning the mechanisms of natural selection. First, one inferential folk bias results in a focus on *similarities* across members of the same, and related, species (Atran, 1998). This bias facilitates the functional goal of being able to predict the behavior (e.g., growth patterns) of these plants and animals, as related to procuring food and medicines. At the same time, the focus on within-species similarities runs counter to the insight that within-species differences, or variability, provide the grist for natural selection. Second, folk biological knowledge is also implicitly focused on the behavior of flora and fauna at different points in a single life span (e.g., maturity of a plant, relative to when it is best to harvest) and not the cross-generational time scale over which natural selection operates. In other words, people are biased to think about and understand the biological world in ways that are functional in natural settings and have been beneficial during our evolutionary history, but these biases also interfere with understanding the mechanisms of natural selection.

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Research in evolutionary educational psychology will focus on identifying such biases, generating explicit comparisons between these biases and scientific concepts in the same domain, and assessing alternative instructional approaches to correcting these naïve beliefs (e.g., Hunt & Minstrel, 1994).

The reliance on the brain and cognitive systems supporting attentional control, working memory, and conflict resolution during scientific reasoning and when comparing experimental data with conceptual models can be integrated into my motivation to control model. More precisely, the historical emergence of science and the ability to learn science in the modern classroom is predicted to be dependent upon the conscious psychological and cognitive systems that evolved to cope with variant social and ecological dynamics. As described in the section Motivation to Control, the combination allows for the explicit generation of mental models of past, present, and potential future states in working memory. These representations are predicted to be centered on social (e.g. group conflict), ecological (e.g., hunting), or physical (e.g., climate change) conditions and to access folk knowledge in the respective domains of psychology, biology, and physics. Everyday problem solving (e.g., use of analogy, induction) represents the constraints and biases in how mental models of these situations are manipulated in the problem space to generate control-related behavioral solutions to novel, dynamic situations (Geary, 2005).

In other words, because scientific knowledge and the scientific method are evolutionarily novel cultural innovations, the brain and cognitive systems that evolved to cope with novelty—including a bias to construct mental models that include mechanisms (often incorrect) of how and why the phenomena of interest operates in the world—are predicted to be engaged in the generation of scientific knowledge and in the learning of this knowledge. If this is correct, then an understanding of these conscious psychological mental models might provide insights into how naïve folk knowledge is represented and manipulated in working memory when children and adults construct models of the world and how these same mechanisms might be used to modify naïve concepts and better teach the corresponding scientific concept. As noted, naïve folk biological knowledge may include construction of mental (or explicitly represented) models of species' change but these changes tend to be constrained to individual lifetimes and to minimize individual differences (Shtulman, 2006; Wellman & Gelman, 1992). To understand the mechanisms of natural selection, these mental models need to be expanded to include individual variation within and change across lifetimes. In this way, the teaching of natural selection involves modification of existing, naïve concepts.

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If learning of evolutionarily novel information, including components of natural selection, involves use of explicit mental models, attentional control, and working memory, then several predictions follow: (a) children's conceptual understanding will be facilitated if they are able to construct a mental model of how and why the phenomena of interest operates; (b) construction of any such models will be initially based on folk knowledge and modifications of these concepts will be facilitated if folk assumptions are made explicit and directly compared and contrasted with the corresponding scientific concept; and (c) conceptual change will require repeated exposures to the new concepts, especially for concepts that conflict with folk beliefs. Included among the latter are beliefs about human agency, origins, social motives, and so forth; scientific knowledge that contradicts evolved folk psychological biases are predicted to be especially difficult to teach.

### ***Individual Differences in Secondary Learning***

Individual differences in the ease of secondary learning are well known and often a source of educational and political debate (Benbow & Lubinski, 1996; Benbow & Stanley, 1996; Ceci & Papierno, 2005). The source of these individual differences is multifold, and includes many of the traits associated with eminent achievement noted in the section titled Human Intellectual History and the Creation of Culture, including individual differences in *gF*, motivation, hours worked, and opportunity (Lubinski, 2004). Variation in these traits is expected from an evolutionary perspective, and thus individual differences in secondary learning are expected as well. The central educational and political debate centers on this variation and whether the variation is consistent with the cultural more of "equality." The nuances of this debate are lucidly addressed by Ceci and Papierno, and thus do not need attention here. Rather, I wish to echo the concerns raised by Benbow and Lubinski regarding the consequence of attempts to achieve equity in educational outcomes. More precisely, the focus on attempts to reduce individual differences in educational outcomes, that is, individual differences in secondary abilities and knowledge acquired in school and elsewhere, have focused on improving the learning of low achieving students. From an evolutionary perspective, these are exactly the students who are predicted to need well-organized, explicit and often teacher driven instruction for efficient secondary learning. But, the focus on the learning needs of these children and the implicit goal of achieving equality of outcomes has come at a cost to the educational and long-term occupational potential of many children who are toward the high end (> 90th percentile) on measures of *gF*.

Indeed, if the evolved function of *gF* is to cope with and learn about evolutionarily novel information patterns, then children and adults who

are high in *gF* should require less formal instruction than other people to achieve the same level of secondary abilities and knowledge. This is because learning in school is all about acquiring evolutionarily novel abilities and knowledge, and because individuals who are high in *gF* have an enhanced—and evolved—ability to learn novel information rapidly and on their own. Not only is the rate of secondary learning of these children accelerated, the experiences that result in the achievement of their full educational potential differs in important ways from that of other children (see Benbow & Lubinski, 1996; Bleske-Rechek et al., 2004). For instance, the finding that phonemic and word decoding skills are most effectively acquired through explicit and teacher directed instruction (Hindson et al., 2005; Wagner & Torgesen, 1987), does not apply to many intellectually gifted children. Many of these children show greater school-year gains in reading when allowed to work independently (e.g., silent reading), presumably because they have acquired basic phonemic and decoding skills earlier than most other children (Connor et al., 2004). Because children high in *gF* learn novel information more rapidly than other children, it follows that full engagement of these gifted children in schooling and to achieve their full educational potential will require acceleration through the typical curriculum as well as a more complex curriculum (Bleske-Rechek et al., 2004).

From the perspective I have outlined here, facilitating the educational and occupational achievement of these individuals is important for any culture, because scientific, technological, and other cultural innovations are disproportionately produced by these individuals. On the basis of historical patterns (Murray, 2003), cultures that facilitate the ability of these individuals to learn complex cultural innovations (e.g., become physicians, lawyers) and to create new innovations will be advantaged relative to other cultures. In other words, attempts to achieve within-culture “equity” may come at a long-term cost in terms of the ability to compete with other cultures.

## CONCLUSION

In modern societies today, there are formal institutions, such as research universities and commercial laboratories, that are designed to be engines of cultural, artistic, and scientific innovation and for the generation of new knowledge. When viewed from the lens of human evolution, these cultural institutions and the resulting explosion of biologically secondary knowledge are unique and very recent phenomena. Although these advances have resulted in extraordinary benefits (e.g., reduced infant and child mortality), they have also created equally extraordinary demands on

our ability to fully understand and cope with this new knowledge. One of the changes that has emerged in these cultures is an accompanying need for other formal institutions, especially schools, that function to prepare children for the evolutionarily novel demands of living and succeeding in these societies. In fact, the need to educate children for these demands is going to accelerate, because more and more institutions of knowledge generation are likely to emerge in coming decades and will result in an exponential increase in secondary knowledge. Because formal schooling and the need to teach recent cultural innovations to children are themselves evolutionarily novel, adults are not expected to intuitively understand how to best proceed with this endeavor (Geary, 1995). As part of their folk psychological repertoire, adults may intuitively know how to use stories and modeling to impart to children knowledge and competencies that have been useful in more natural environments and in kin-based social groups. But, this intuitive repertoire is no longer sufficient and because of this, considerable confusion, conflict, and derision among competing educational approaches is predicted and found (e.g., Hirsch, 1996; Loveless, 2001; Egan, 2003).

By placing the field of education on a more scientific foundation, an evolutionary approach will reduce these conflicts. Evolutionary developmental psychology and accompanying insights into children's cognitive development and motivational biases will provide the first level of this foundation (Bjorklund, *in press*; Geary & Bjorklund, 2000). From this perspective, cognitive development is an inherent feature of the human life span, and represents the fleshing out of the plastic features of modularized folk domains such that these brain and cognitive systems become sensitive to nuances in the local social, biological, and physical ecologies (Geary, 2004). The experiences needed to adjust these folk systems to these ecologies are generated by children's natural social play, exploratory activities, and adult-child interactions. The result of these activities is the effortless and automatic adaptation of folk systems such that the child easily makes discriminations among different people and learns about their personality and behavioral dispositions; forms categories of local plants and animals and learns about their essence; and, develops mental maps of the group's physical territory, among many other cognitive changes (Wellman & Gelman, 1992). These cognitive competencies are biologically primary, that is, the human mind is inherently biased to acquire knowledge in these domains and to do so with little effort.

Academic development, in contrast, involves the experience-driven acquisition of nonevolved, or biologically secondary cognitive competencies (Geary, 1995). The acquisition of these competencies is dependent on plasticity in modularized folk domains, and the existence of domain-general mechanisms that evolved to enable the adaptation of these folk sys-

tems to evolutionarily novel information. An example of the latter was provided with my discussion of how associations among language sounds and visual patterns are formed to create the ability to read and write. Although not typically approached from an evolutionary perspective, research in experimental psychology has identified these domain general systems; specifically, general fluid intelligence (Kane & Engle, 2002). Fluid intelligence is composed of the attentional and working memory systems that enable people to explicitly represent and manipulate information that has tended to be variable during human evolutionary history, and thus is to some extent evolutionarily novel. It appears that the explicit representation of information in working memory and the reasoned manipulation of this information are at the heart of the human ability to construct non-evolved cognitive competencies (Ackerman, 1988) and thus are the core cognitive mechanisms underlying the maintenance and generation of human culture.

From an evolutionary perspective there are several key points: First, secondary learning is predicted to be heavily dependent on teacher- and curriculum-driven selection of content, given that this content may change across and often within lifetimes. Second, for biologically primary domains, there are evolved brain and perceptual systems that automatically focus children's attention on relevant features (e.g., eyes) and result in a sequence of attentional shifts (e.g., face scanning) that provide goal-related information, as needed, for example, to recognize other people (Schyns, Bonnar, & Gosselin., 2002). Secondary abilities do not have these advantages and thus a much heavier dependence on the explicit, conscious psychological mechanisms of the motivation-to-control model—Ackerman's (1988) cognitive stage of learning—is predicted to be needed for the associated learning. Third, children's inherent motivational biases and conative preferences are linked to biologically primary folk domains and function to guide children's fleshing out of the corresponding primary abilities (see Figure 1.2). In many cases, these biases and preferences are likely to conflict with the activities needed for secondary learning.

Although these conclusions might seem obvious to some readers and not in need of an evolutionary framework, such a framework might have obviated the often rancorous debate on how to most effectively teach children, for instance, how to read (e.g., Loveless, 2001). These debates have waxed and waned without resolution for nearly 250 years, since Rousseau's 1762 publication of *Emile*. Of course, Rousseau and other philosophers of education did not have an evolutionary theory in place to guide their thinking about these issues. But, this is no longer the case. My point here is that we do not have to repeat this contentious process for each and every academic domain, if there are foundational principles in place for understanding secondary learning in general.

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