Taming Uncertainty

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16 How the Adaptive Adolescent Mind Navigates Uncertainty

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16.1 The Turbulent Period of Adolescence

At a turning point in the classic coming-of-age movie *Rebel Without a Cause* (Weisbart & Ray, 1955), two teenagers stand at the edge of a cliff and gaze into the abyss. Buzz, the local bully, has just explained to Jim, the new kid on the block played by James Dean, the game of "chickie run." Each of them will race a stolen car toward the edge of the cliff, jumping out at the last minute. The game is a test of courage: whoever jumps first is a chicken. Before heading to their cars, Jim asks Buzz, "What are we doing this for?" Buzz seems puzzled by the question. After giving it some thought, he replies, "We got to do something. Don't we?" But that something goes wrong. Buzz's jacket sleeve gets caught on the door handle; he cannot escape in time. The car plunges over the cliff.

Colloquially, human adolescence means the teenage years. Scientifically, it covers a broader and somewhat more flexible period of development, starting with the onset of puberty (see box 16.1) at about 10 years of age and ending whenever a culture considers an individual to have become an adult. During this turbulent period, adolescents have to navigate a novel and inherently uncertain environment while at the same time learning to take on adult roles and responsibilities. As *Rebel Without a Cause* illustrates, adolescence is often portrayed as a period of wildly erratic behavior. The empirical data are consistent with this impression: mortality and morbidity caused by risky and impulsive behaviors increase in adolescence. In the United States, for example, nearly 75% of deaths in the second decade of life result from unintentional injuries incurred in circumstances such as car accidents, poisoning and drug overdose, drowning, and the discharge of firearms

Box 16.1
Pubertal hormones.

Adolescence starts in biology and ends in society. It begins with the onset of puberty, which is characterized by a rapid increase in gonadal hormone release. The sex hormones testosterone, estradiol, and dehydroepiandrosterone initiate development of secondary sexual characteristics, such as facial hair, and boost physical growth. Puberty is triggered by both internal and external cues providing information on the availability of resources required for successful reproduction. Internal cues include metabolic levels of insulin, glucose, and leptin, which indicate somatic growth and metabolic fuel availability. External cues include information on the harshness and unpredictability of the environment (e.g., availability of mates and scarcity of resources). In a stable environment with plenty of resources, puberty may start later because an individual can afford to grow big and healthy before investing all their energy in procreating. In a harsh environment characterized by periods of severe weather, food shortages, and unpredictable conditions, in contrast, puberty occurs earlier (Sapolsky, 1997), and individuals' risk propensity remains stable across the adult life span, attenuating the typical decline in risk-taking behavior associated with old age (see chapter 17). Research on which environmental aspects lead to early onset of puberty is currently scarce, but understanding these processes is of high societal relevance: early entry into puberty (relative to same-aged peers) is associated with psychosocial problems throughout adolescence (Copeland et al., 2010) and with vulnerability to a wide range of psychological disorders (Mendle & Ferrero, 2012).

(Mulye et al., 2009). Although 15- to 24-year-olds represent only a quarter of the sexually active population, nearly half of all sexually transmitted diseases (48%) occur in that age group (Satterwhite et al., 2013) and there is a dramatic rise in criminal behavior in adolescence, peaking at the age of 19 before declining again in young adulthood (the age–crime curve).

It is as if adolescents are magically drawn to the edge of the cliff. However, not all adolescents are inclined to act self-destructively or turn into criminals—most will never come into contact with the law. And, for the most part, they will emerge from the other side of adolescence: slightly more than 99.9% of North American teenagers, for instance, survive this tumultuous time (Willoughby, Tavernier, Hamza, Adachi, & Good, 2014). But there is converging evidence that the occurrence of adolescent typical behavior, in some form or another, is historically and culturally invariant (e.g., Schlegel & Barry, 1991). It is this higher propensity for risky, impulsive, and dysfunctional behavior that has led countless writers, researchers, and parents to believe that there is something fundamentally wrong with adolescents, who seem to be afflicted by some temporary form of irrationality. Yet adolescence as a distinct developmental period has roots not only in human history—it has also been described in numerous other animals, including mammals and birds. Taken together, this evidence suggests that adolescent behavioral characteristics, including increased impulsive and exploratory behavior, may have had adaptive functions across evolutionary history (Spear, 2000). Consequently, we take an evolutionary perspective on adolescent behavior under uncertainty. This approach offers a different view on the irrational adolescent and emphasizes the potential benefits of an ecological analysis for understanding adolescent behavior. Drawing on life-history theory (Kaplan & Gangestad, 2005; Stearns, 1992), we discuss two types of evolutionary mechanisms that may explain how adolescent behavior emerges in response to environmental properties, and review supporting evidence for each. Finally, we outline how an ecological analysis raises new research questions that could, if explored, help young people navigate their teenage years.

We should emphasize that an adaptive framework of adolescent behavior does not fall into the Panglossian trap of claiming that everything adolescents do is good or beneficial for them. For instance, there may be a mismatch between the *environment of evolutionary adaptedness* (Bowlby, 1969), specifically the developmental niche, and the current adolescent environment. As a result, evolved behavioral tendencies may not optimally contribute to the overall fitness of a 21st-century adolescent. A classic example of such a mismatch is the preference for fatty, sweet, and salty foods, which evolved in an environment where food, calories, and salt were scarce. These preferences are increasingly dysfunctional in today's obesogenic environment (see chapter 6).

16.1.1 The Ecological Rationality of Adolescent Behavior

In the decision sciences, the ecological rationality framework proposes an intimate fit between mind and environment (Simon, 1956; Todd, Gigerenzer, & the ABC Research Group, 2012). By exploring how minds fit environments, researchers studying ecological rationality aim to specify the structure of information-processing mechanisms, the structure of information available in the environment, and the way the two structures fit together. Mapping out particular aspects of the decision maker's environment allows researchers to ask specific questions regarding the mind. Whereas the environment may often seem more or less immutable from the decision maker's point of view, the capacities (including cognitive and behavioral strategies) of the cognitive system will be shaped—by evolution or development—to take advantage of the structure of the external environment (Todd & Brighton, 2016). From this perspective, adolescents' behavior results from the interaction of immediate environmental demands and affordances on the one hand, and the cognitive capacities and motivational states of the developing individual on the other. In addition, the observed cognitive capacities and motivational states are expected to drive patterns of behavior that have evolutionary advantages (i.e., promoting inclusive fitness). Thus, to fully understand adolescent behavior, researchers need to not only consider ontogenetic, or individual, development, but also to adopt a phylogenetic perspective that considers how recurrent properties of the ancestral environment shaped the adolescent mind.

Here we will discuss two such mechanisms. First, life history theory posits that developing organisms adopt different behavioral strategies in response to fitness-relevant properties of the environment and changes therein. Specifically, it suggests that *fast life history strategies*—including the increased risky and impulsive behavior so typical of adolescence—represent responses to higher levels of environmental uncertainty and harshness. Second, explanations based on *ontogenetic* and *deferred* adaptations do not postulate that the level of uncertainty per se is more pronounced for adolescents than it is for children or adults. Rather, they propose that adolescents show systematically different responses when confronted with the same level of uncertainty. Ontogenetic adaptations are behavioral patterns that are tuned to the specific environment of the organism's developmental stage; deferred adaptations prepare adolescents for later developmental stages (e.g., adulthood). All these possibilities highlight that the developmental changes in cognitive and affective capacities observed in adolescence are not immature stages of adult functioning but may represent specific responses to environmental properties and demands unique to that developmental stage.

16.2 Life History Theory: Live Fast, Die Young, or Live Long and Prosper?

According to the evolutionary perspective on human development, neurobiological mechanisms adaptively calibrate behavioral strategies across the life span, allowing the individual to navigate the current developmental niche and to anticipate future environments (Kaplan & Gangestad, 2005). Specifically, *conditional adaptations* are thought to respond to relevant environmental cues, altering developmental pathways in ways that are better adapted to the current or future environment. Life history theory, a framework with origins in developmental biology, suggests that behavior across the life span can be explained in terms of evolved strategies for distributing metabolic resources between the competing demands of growth, maintenance, and reproduction. These strategies are thought to lie on a continuum from "slow" to "fast," where "species on the fast end exhibit short gestation times, early reproduction, small body size, large litters, and high mortality rates, whereas species on the slow end have the opposite features" (Kaplan & Gangestad, 2005, p. 73). Humans are paradigmatic representatives of the "slow" track, whereas smaller mammals, such as rodents, are at the fast end of the continuum. The course of a life history strategy varies not only across species, but also across individuals within a species. It follows that ontogenetic differences in strategies are the result of individual differences in the experienced environment (Fabio, Tu, Loeber, & Cohen, 2011). Furthermore, different life history strategies may also arise from the environments experienced across the life span.

Life history theory identifies two environmental dimensions that drive the fast versus slow dynamic—namely, harshness and unpredictability (or uncertainty; Ellis, Figueredo, Brumbach, & Schlomer, 2009; Frankenhuis, Panchanathan, & Nettle, 2016; see figure 16.1). Harshness refers to conditions with a negative impact on fitness, caused by factors over which the individual has no control. For humans, poverty and low socioeconomic status (i.e., resource scarcity) can represent harsh conditions that not only lead to hunger and malnutrition, but are also associated with high crime rates and heightened vulnerability to disease. Uncertainty may be due either to variance in the level of harshness (what will happen) or to differences in the spatial or temporal location of outcomes (where and when things

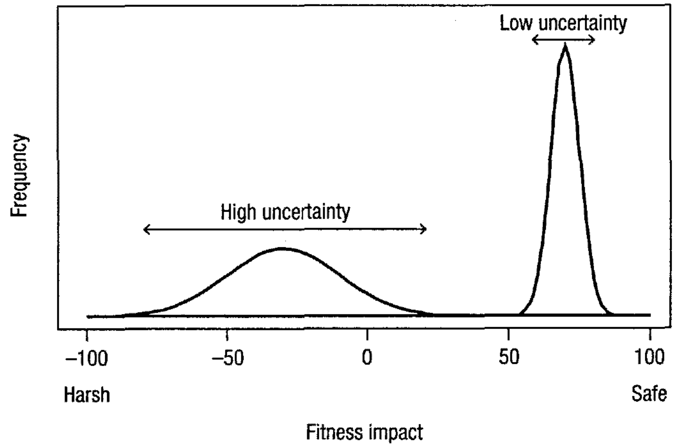

Figure 16.1
Two hypothetical frequency distributions of fitness-relevant events in the local environment. The distribution on the left has a negative mean and a large variance. It is both harsh and unpredictable. The distribution on the right represents a safe and predictable environment (see also Frankenhuis et al., 2016).

happen). More contemporary examples of environmental unpredictability include residential moves, job changes, and changes in the relationships of parents (e.g., separation, divorce, and new partners). These environmental changes often entail transitions to new social circles.

Both harshness and uncertainty push an organism to select "fast" strategies: the shorter one's expected reproductive life span, the greater the benefits of accelerating maturation and reproducing early, even if it compromises longevity (Kaplan & Gangestad, 2005). Research has shown that environmental uncertainty during early childhood predicts earlier onset of puberty and reproduction in humans; similar patterns have been observed in other animals (Ellis et al., 2009). Life history strategies may also be reflected in specific psychological mechanisms. For instance, present-orientation, that is, a preference for present over future rewards, may be adaptive in harsh and uncertain environments (Fawcett, McNamara, & Houston, 2012; see chapter 9). In these contexts, organisms are expected to prioritize the fitness benefits of immediately available rewards (e.g., by increasing access to mates) at the expense of future rewards, which are less likely to be received. Indeed, exposure to uncertain environments predicts present-orientation in diverse populations, including children and adolescents (Frankenhuis et al., 2016). For example, Mischel observed that 7- to 9-year-old children from single-parent households—burdened, all other things being equal, with increased uncertainty—were more likely to choose a small immediate reward over a larger one promised at some time in the future (Mischel, 1961; but see also Watts, Duncan, & Quan, 2018). By the same token, adult women who reported more early-life stress reported a shorter expected life span (e.g., higher future uncertainty) and a younger age of first sexual intercourse (Chisholm, 1999). Although harshness and uncertainty often go hand in hand, several studies have shown that the two dimensions can have unique effects on life history strategies (Doom, Vanzomeren-Dohm, & Simpson, 2016).

Thus, life history theory suggests that there is a universal mechanism that determines how environmental signals prompt organisms to choose adaptive life history strategies across the life span. Most of this work has focused on how early-life stress, in the first few years after birth, triggers a shift toward the fast end of the continuum that often becomes manifest in adolescence or young adulthood. However, early-life stress in itself does not explain the adolescent-specific pattern of a rise and fall in behaviors associated with fast life history strategies. Let us think back to the age–crime curve mentioned earlier. The rise in arrests in early adolescence may be partly explained by adolescents having more opportunities than children to break the law, as they are less subject to parental oversight. Given that this rise in crime is only caused by a subset of adolescents, one could hypothesize that those are the ones that experienced early-life stress. But even then, life history theory does not explain why there would be a decline in criminal behavior observed in late adolescence/young adulthood. In contrast, early-life stress is a good predictor of criminal behavior that persists beyond adolescence (Brumbach, Figueredo, & Ellis, 2009). Thus, there must be a different explanation for the adolescents who show an increase followed by a decrease in criminal behavior.

This pattern of adolescent behavior can be explained as a conditional adaptation within the life history theory framework only if two requirements are met. The first is a systematic shift in the uncertainty of the environment during adolescence—specifically, a sudden increase in uncertainty (and/or harshness) in early adolescence, followed by a decrease in mid/late

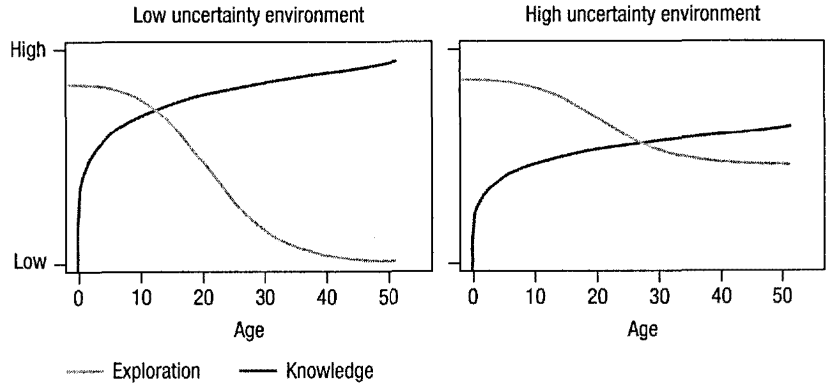

Figure 16.2
In a stable environment (left panel) there is a benefit of increased exploration which declines the more is learned about the environment. Thus, as knowledge is reaching a plateau, the need for exploration is going down. In contrast, in more volatile and unpredictable environments (right panel) the need to explore never truly declines and there is a limit to the knowledge one can ever have about the world (for similar ideas see Gopnik, Griffiths, & Lucas, 2015; Romer, Reyna, & Satterthwaite, 2017).

adolescence. For instance, the transition to high school and a new social group may create a volatile, uncertain environment that stabilizes over time. Note, however, that the level of uncertainty about the environment is also related to learning. For example, in a relatively stable environment, the overall level of uncertainty is likely to decline with age and experience (see figure 16.2). As a result, the need for exploratory behavior will decrease. Following this logic, a gradual decline in typical adolescent behavior toward the end of adolescence may be rendered possible by past behavior (e.g., exploration). In a relatively stable environment, risky explorative behavior becomes increasingly obsolete because the individual knows what to expect. The second requirement for explaining typical adolescent behavior as a conditional adaptation is that there is significant plasticity in the adjustment of life history strategies across adolescent development (speeding up or slowing down). It remains unclear whether these two conditions apply. There is evidence for increased neural plasticity during adolescence (see box 16.2), but little is known about the changing levels of uncertainty of the typical adolescent environment. We will address this question in section 16.2.1.

Box 16.2
Adolescent brain development.

Cerebral alterations in adolescence are characterized by early maturation of the subcortical motivational system, but slower development of the prefrontal top-down control mechanisms (Somerville & Casey, 2010). More generally, neurons, synapses, and receptors are overproduced during the transition from childhood to adulthood and undergo dramatic rearrangement with increasing age, resulting in reduction of gray matter through pruning (Luna, Paulsen, Padmanabhan, & Geier, 2013). Furthermore, white matter tracts—the links between neurons—develop across almost the whole brain throughout childhood and adolescence into adulthood (Luna et al., 2013). The constant refinement of the neural architecture during adolescence is also related to changes in cognitive abilities (e.g., working memory and problem solving) and social cognition (e.g., perspective taking). In view of these specific neural changes, it has been argued that this developmental period may be a sensitive period for the shaping of sociocognitive skills (Fuhrmann, Knoll, & Blakemore, 2015). Adolescence is already known to be a delicate period in terms of the effects of stress on mental health. Psychiatric disorders such as depression or schizophrenia have their onset in adolescence (Paus, Keshavan, & Giedd, 2008) and can be triggered by stress exposure. Taken together, the high level of neural plasticity during adolescence seems to coincide with the development of higher cognitive and social functioning. The flip side of this plasticity-related learning potential is that stress or other environmental deprivation may have pronounced and long-lasting effects.

With respect to the development of brain function, neuroimaging studies have shown that adolescents show higher subcortical activity than adults (see Silverman, Jedd, & Luciana, 2015 for a meta-analysis). For instance, the ventral striatum has been shown to be more responsive to rewards in adolescents than in children and adults. This increased level of activation has been linked to self-reported risk taking and sensation seeking and is even more exaggerated in the presence of peers (Albert, Chein, & Steinberg, 2013). Furthermore, the increased engagement of the valuation network is hypothesized to lead to an increase in social motivation (Crone & Dahl, 2012). Indeed, studies with both adult humans and rats have shown that striatum activity is associated with greater susceptibility to, and drive to learn from, social information (Klucharev, Hytönen, Rijpkema, Smidts, & Fernández, 2009).

Finally, pubertal hormones such as testosterone also impact the developing brain (Laube & van den Bos, 2016; Schulz & Sisk, 2016). It has been suggested that pubertal hormones are crucial in initiating a sensitive period for social and motivational processing in adolescence (Crone & Dahl, 2012). For instance, impatient behavior in boys is related to pubertal stage measured not in terms of chronological age, but in terms of testosterone levels (Laube, Suleiman, Johnson, Dahl, & van den Bos, 2017), and testosterone levels in adolescent girls predict sensitivity to social status (Cardoos et al., 2017).

16.2.1 Adolescence: An Age of Uncertainty?

> "Who are you?" said the Caterpillar. Alice replied, rather shyly, "I—I hardly know, sir, just at present—at least I know who I was when I got up this morning, but I think I must have changed several times since then."
>
> —Lewis Carroll, *Alice's Adventures in Wonderland*

The story of *Alice's Adventures in Wonderland* captures a great deal of the bewilderment of adolescence. Alice's body has taken on a will of its own, growing and shrinking. More generally, the world around her seems to be operating on the basis of a set of irrational rules, causing Alice to question her identity. Adolescence is indeed a period of major upheaval. On their path to independence, adolescents begin to separate from their parents and from other caregivers with whom they have spent most of their waking hours. They now have more autonomy to choose what to do, when to do it, and with whom. But the path to independence is fraught with uncertainty. The social world changes profoundly during adolescence, a time when teenagers often move to a new school and have to fit in with a new group of peers. As they reach sexual maturity (Suleiman, Galván, Harden, & Dahl, 2017), they enter into their first romantic relationships, and friendships take on more profound forms. During this period, adolescents become more aware of, and preoccupied by, the structure of the peer group and their place in it (Coleman, Herzberg, & Morris, 1977). The new peer group becomes a developing adolescent's main framework. Finding out how this new social world works, who they are, and where they fit in—that is, positioning themselves within the social hierarchy—is a major developmental task for adolescents. One's position in the social hierarchy is likely to impact one's future success and, in evolutionary terms, even their potential overall fitness (von Rueden, Gurven, & Kaplan, 2011). Yet researchers know relatively little about how uncertainty about the adolescent social world affects young people's behavior and development.

Along with their path to independence, an adolescent's future itself is also fraught with uncertainty. The promise of independence may seem appealing but it also brings many unknowns. What will I do after school? What job will I work in? How much money will I make? Who will be my partner? Uncertainty about these prospects may also contribute to adolescents adopting faster life history strategies. For instance, U.S. adolescents have been shown to overestimate their probability of dying in the next year by 18.6% (base rate: 0.1%; Bruine de Bruin, Parker, & Fischhoff, 2007). Mortality estimates were even higher for adolescents who reported having experienced personal threats (e.g., living in an unsafe neighborhood; Fischhoff, Bruine de Bruin, Parker, Millstein, & Halpern-Felsher, 2010). This finding suggests that there is meaningful variability in these overestimates, and that the degree of misjudgment is linked to environmental variables. Consistent with life history theory and the notion that future uncertainty promotes fast life history strategies, Bruine de Bruin and colleagues also found that the more teenagers overestimated their probability of dying, the more risky behaviors they reported (McDade et al., 2011). It is possible that similar effects will be observed for less dramatic—but still fitness-relevant—future uncertainties.

It would be premature to claim that adolescence represents a unique age of uncertainty in terms of sheer quantity. But the quality of uncertainty during adolescence may indeed be unique. A systematic investigation of adolescents' *Umwelt* (Uexküll, 1992)—that is, their subjective environment, which is a function of the cognitive and sensory machinery—would cast light on the kinds of uncertainties specific to adolescence, as well as their sources. One domain of adolescent life in which little is certain and much is to be discovered is the novel social world. Ecological analyses of this social environment would open several interesting avenues for further research (see section 16.4). But it is important not to overlook another important possibility. The Umwelt in which adolescents find themselves may be just as uncertain as the Umwelt of children or adults. The crucial difference may lie in adolescents' response to that same environmental uncertainty—the reason being that their learning objectives are different. We turn to this possibility in section 16.3.

16.3 Ontogenetic and Deferred Adaptations in Adolescence

A developmental niche is a period in an organism's life span characterized by unique demands and affordances. It is thus possible that some behaviors that are more pronounced in adolescence than in other developmental periods are *ontogenetic adaptations*: behaviors and mechanisms that adapt an organism to its current (as opposed to its future or past) developmental niche (Geary & Bjorklund, 2000). Ontogenetic adaptations are not immature forms of adult adaptations; they may even "disappear" when no longer necessary. For instance, it has been proposed that neonatal imitation of facial expressions (e.g., tongue protrusion) is an ontogenetic adaptation designed to foster infant–mother interaction at a moment in development at which infants have little intentional control over their behavior (Bjorklund, 1997). Another example of an ontogenetic adaptation in childhood is the tendency of children to overestimate their abilities, which enables them to keep motivated on difficult learning tasks (Bjorklund, 1997). Along the same lines, it is possible that typical adolescent behavioral patterns, such as risk taking and sensation seeking, have specific fitness benefits at this particular stage of life. *Deferred adaptations*, in contrast, are future-oriented adaptations to the extent that their benefits are delayed and occur in the future (e.g., the adult developmental niche). For instance, gender differences in rough-and-tumble play in childhood itself do not increase the direct chances of survival; in fact, survival chances may even decrease due to minor injuries. However, this type of play is thought to be an essential preparation for adult social life (Pellegrini & Bjorklund, 2004).

Consistent with these ideas, it has long been argued that typical adolescent risk and impulsivity attitudes have adaptive functions, giving adolescents the drive to learn the new skills needed to navigate the challenges of adult life (Csikszentmihalyi, Larson, & Prescott, 1977). Adolescent animals often have to leave the nest and explore novel, potentially dangerous, environments in the search for food and mates. They have to take risks when testing their strength against competitors (Bercovitch et al., 2003). Succeeding in these developmental tasks may directly contribute to their survival by providing increased access to food resources (ontogenetic adaptation). However, adolescent behavior may also have benefits that materialize only in the future (deferred adaptations)—in other words, the learning that occurs during adolescence pays off later in life. Phelps et al. (2007) also found evidence that high scores on risk and problem behaviors among adolescents are associated with positive developmental trajectories (e.g., increasing social competence, caring, confidence, and character).

Feeling less anxiety about the unknown may have adaptive functions for adolescents. Adolescence is about learning to become an independent agent (Sercombe, 2014). For the first time, learning new skills and discovering novel environments takes place largely without parental guidance and oversight. Exploring a novel environment may lead to the discovery of new niches and opportunities (e.g., food resources, social alliances, and reproductive partners). But it can also be dangerous—and a cause of anxiety—due to social and physical risks. Animal studies have shown that an increased exploratory drive in adolescent mammals is paralleled by a reduction in uncertainty-related anxiety. For instance, Macri, Adriani, Chiarotti, & Laviola (2002) compared the exploratory behavior of juvenile, adolescent, and adult mice in a radial maze with open and enclosed arms. Juvenile and adult mice strongly avoided the maze's open arms, whereas the adolescent mice spent equal time in the open and enclosed arms. They also showed less anxiety when out in the open than juvenile or adult mice. These findings suggest that temporary reduction in anxiety about the unknown may be an ontogenetic or deferred adaptation during adolescence, fostering a higher intensity of exploratory and risk-taking behavior. Unfortunately, data on these temporal dynamics are sparse and longitudinal studies of mice and humans are lacking.

16.3.1 Developmental Differences in Navigating Uncertainty: Empirical Evidence

Both ontogenetic and deferred adaptations can lead to an adolescent-specific pattern of behavior, but is there any evidence that adolescents are less averse to uncertainty than adults and children? There have been surprisingly few studies of adolescents' behavior under uncertainty. Instead, most experimental studies have presented adolescents with choice problems in which they are forced to make a selection between one of two options. Both are fully described in terms of the potential outcomes and associated probabilities (see figure 16.3a). In reality, such situations are rare; people seldom know everything there is to know about an upcoming decision. In this sense, common experimental designs are "strange situations" that fail to capture the environment or the choices adolescents actually face (Bronfenbrenner, 1979). It is therefore not surprising that this type of experimental study has regularly failed to reproduce the typically adolescent patterns of risk behavior that are so striking in the real world (I. N. Defoe, Dubas, Figner, & van Aken, 2015; Rosenbaum, Venkatraman, Steinberg, & Chein, 2018). When adolescents use drugs or engage in unprotected sex, they may have only a vague idea of the possible consequences of their actions because they lack personal experience. Van den Bos and Hertwig (2017) recently examined what happens when adolescents are given the opportunity to "look before they leap"—that is, when they are empowered to search for information

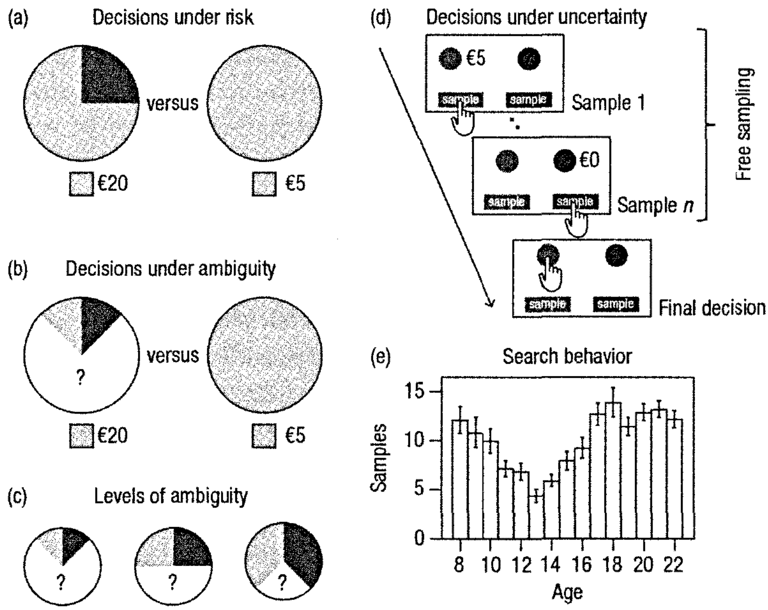

Figure 16.3
Experimental tasks. (a) Decisions under risk were represented by a wheel of fortune consisting of eight slices. If the spinner stopped on a dark gray slice, the player received nothing. If the spinner stopped on a light gray slice, the player won or lost a certain amount of money. (b) Decisions under ambiguity were represented in exactly the same way as the risky gambles, but this time occluders (here in white) on top of the wheels hid part of the information. (c) Three levels of ambiguity were implemented. (d) In the decisions under uncertainty task, participants were able to sample from two payoff distributions before making a final decision. Respondents sampled by pressing the sample button and chose by clicking on the corresponding circle. All experimental tasks were self-paced. (e) Age-related changes in the amount of search in the sampling paradigm. (Adapted from van den Bos & Hertwig, 2017.)

(e.g., by actively probing their peers' experience or observing what happens to others engaging in a risky activity), hence reducing the level of uncertainty, before embarking on an activity. Using a paradigm developed in research on *decisions from experience* (see chapters 1 and 7) to implement conditions more representative of the adolescent ecology, van den Bos and Hertwig asked 105 respondents, ranging in age from 8 to 22 years, to make decisions in three kinds of environments: risky, ambiguous, and uncertain (see figure 16.3).

Decisions under risk are the canonical way to study individuals' risk preference in psychology and economics. Here, full information about the options' possible outcomes and probabilities is provided for free. In *decisions under ambiguity*, the information available on probabilities is incomplete, as is often the case in the real world. Many experimental studies have found that adults tend to be ambiguity averse. In other words, they prefer *known* risks (e.g., an urn of 50 red and 50 green balls, with a reward for drawing a green ball) to *unknown* risks (e.g., an urn with 100 red and green balls in some unknown combination; Ellsberg, 1961; Tymula et al., 2012). In light of typical adolescent behavior, one might expect adolescents to be less ambiguity averse than adults or children. In the *decisions under uncertainty* task, respondents were presented with two options that they could explore as much as they wanted before choosing between them, with the outcome of this decision being incentivized. In this environment, the individual determined how much information to sample before making a final decision. One signature finding from the adult literature is that people tend to sample relatively little information before making a consequential decision (Hertwig & Erev, 2009; Wulff Mergenthaler-Canseco, & Hertwig, 2018; see chapter 7 for details). Given adolescents' propensity to act impulsively, one may expect them to explore less than adults and children—in other words, to be even more accepting of incomplete knowledge about the possible consequences of their actions than other age groups.

Echoing previous experimental results, children appeared to take more risks than adolescents in the canonical decisions under risk measure. For decisions under ambiguity, in contrast, things looked very different. Here, a nonlinear developmental trend emerged, with ambiguity tolerance peaking in adolescence. This result is in line with two previous studies that also found adolescents to be more tolerant of ambiguity than adults (Blankenstein, Crone, van den Bos, & van Duijvenvoorde, 2016; Tymula et al., 2012). A similar nonlinear developmental trajectory in search behavior also emerged for decisions under uncertainty: adolescents searched for markedly less information before making a consequential decision than either children or adults (see figure 16.3e). Here again, they were more tolerant of incomplete knowledge. Moreover, additional analyses (for details, see van den Bos & Hertwig, 2017) suggest that developmental changes in ambiguity and uncertainty attitudes are driven by developmental change in novelty seeking, the personality trait specifically associated with exploratory activity in response to novel stimulation (Arnett, 1994).

In sum, there is emerging evidence that adolescents respond to uncertainty in distinct ways. Their behaviors are consistent with the idea that they are more willing to accept incomplete knowledge and to engage with uncertain environments. However, only a handful of studies to date have examined these behavioral regularities (e.g., Rosenbaum et al., 2018). Furthermore, such a pattern in itself provides supporting evidence for both deferred and ontogenetic adaptations. Next, we set out a road map for further investigation of how adolescents navigate uncertainty.

16.4 Charting the Territory: Where Do We Go from Here?

Adolescent behavioral patterns may be adaptive responses to environmental demands and developmental tasks, such as practicing agency, independence, and autonomy. It is therefore imperative to study the adolescent environment and how the adolescent mind responds to it. Here, we identify two questions for future investigations. First, what is the structure and level of uncertainty in the environments that adolescents seek out? Second, why do adolescents respond differently, relative to other individuals in earlier or later developmental periods, when confronted with uncertainty? The first question requires a thorough ecological analysis of the adolescent environment to map out actual and perceived changes in levels of uncertainty. The second question relates to the motivational and cognitive capacities that may underlie the use of particular strategies for navigating uncertainty.

Eliciting probabilistic expectations would seem to be a promising method for mapping out perceived environmental uncertainty (Bruine de Bruin & Fischhoff, 2017). In this method, people are asked to estimate the probability that a specific event will occur in the near or far future. In combination with experimental and longitudinal data, it can provide insights into how uncertainty increases or decreases across adolescence, what kind of uncertainty is involved, and how these changes affect behavior. Eliciting probabilistic beliefs about single events (e.g., dying within the next five years) can provide a wealth of data. However, the methodology presented in chapter 3 on the *risk–reward heuristic* may offer a richer or at least complementary source of information. As observed in research on this heuristic, people appear sensitive to the structural relationship between risks and rewards in the real world.

Adults tend to rely on mental models of risk–reward structures when making judgments in novel uncertain situations. Building on this research, one could aim to reveal the perceived risk–reward structures of adolescents' environments. Although for adolescents, as for adults, the relationships between risks and rewards are likely to be negative—after all, there really is no such thing as a free lunch—there may be notable differences in the subjective functions describing these relationships. For instance, adolescents do not necessarily judge the probability of detrimental outcomes (e.g., the risk of getting cancer from smoking) more optimistically than adults (Cohn, Imai, Macfarlane, & Yanez, 1995). Instead, it seems that their behavior is driven by the perceived rewards of these risky behaviors (Siegel et al., 1994). These subjective measures are highly relevant given that they predict future engagement in those behaviors (Helfinstein, Mumford, & Poldrack, 2015).

Apart from the subjective perception of uncertainty, it is also worth studying the objective structures of adolescents' environments. Chapter 3 focused on the relation between risks and rewards; let us now consider risk and losses, taking driving behavior as an illustration. Motor vehicle crashes are the leading cause of death for U.S. teenagers. In the United States, six young people aged 16–19 died every day from motor vehicle injuries in 2015 (Centers for Disease Control and Prevention, 2017), and an adolescent is about 2.6 times more likely to be in a fatal accident (Tefft, 2017). However, the odds of being in a fatal accident are low—only about 8 in 100,000 (National Safety Council, 2018). A back-of-an-envelope calculation reveals that the chances of a fatal accident for an adolescent are still very small (23 in 100,000). In other words, a fatal car crash is, luckily, an extremely rare event, even for a teenager. Similar statistics are likely to apply in other risk domains (e.g., there is only a 1 in 33,000 chance of dying in a parachute jumping accident; British Parachute Association, 2018). It is therefore important to understand how adolescents respond to such statistical structures—how do they deal with events that are highly improbable but, if they occur, highly consequential or even deadly (Taleb, 2007)? Could it be that adolescents' behavior differs most strongly from adults' behavior in environments in which rarity and severity join in creating powerful but somewhat veiled risks?

The decisions under uncertainty environment (see figure 16.3d) involving sequential sampling is a valuable tool for uncovering how people respond to environments featuring rare events (Wulff et al., 2018). For instance, there is evidence that when people experience rare events in the sequence of sampled outcomes, they choose as if those events have less weight than they deserve in light of their objective probabilities (see chapters 7 and 8). It is possible that adolescents underweight rare events to an even greater extent than adults. One of the mechanisms behind this underweighting pattern is reliance on very small samples—in which rare events are, by definition, unlikely to occur. More generally, experience-based experimental paradigms (see Hertwig & Erev, 2009) offer novel ways to investigate adolescent behavior under uncertainty. Research on decisions from experience provides many examples of how adults adjust their search as a function of cognitive, emotional, strategic, and environmental variables (Wulff et al., 2018). For instance, adult decision makers increase their sample size (a) in the presence of negative events (Lejarraga, 2010; see chapter 7), (b) when they operate in a state of fear (Frey, Mata, & Hertwig, 2014), and (c) when the number of options increases (Noguchi & Hills, 2016). Furthermore, decisions from experience rely on learning and memory processes and therefore forge a bridge between research on behavioral decision making and neuroscience-based research on basic reinforcement learning processes. The latter has, for instance, observed significant changes in learning skills across adolescence (van den Bos, Cohen, Kahnt, & Crone, 2012).

When investigating adolescent environments, it is vital to consider what is perhaps the most important environment to teenagers: the peer group (van den Bos, 2013). Adolescents spend most of their time with peers, and most typical adolescent behavior occurs in the presence of peers. For many serious crimes, co-offending is more common than offending alone (Zimring & Laqueur, 2015), and car accidents are more likely to occur with peers on board (Chen, 2000). The social environment offers new sources of uncertainty and they are likely to impact adolescents' behavior. Take, for instance, explorative behavior in competitive social environments: the presence of competitors can significantly reduce search efforts, to the extent that people sample only minimally before making a final decision (see chapter 12). Adolescents might be even more willing to act in haste, rush to conclusions, and take risks in the presence of their peers (Albert et al., 2013).

To the extent that the social structure of the adolescent peer network is subject to competition, a hierarchical organization will emerge that may, in turn, also contribute to specific behavioral patterns. For instance, hierarchically organized social structures are often associated with a winner-takes-all

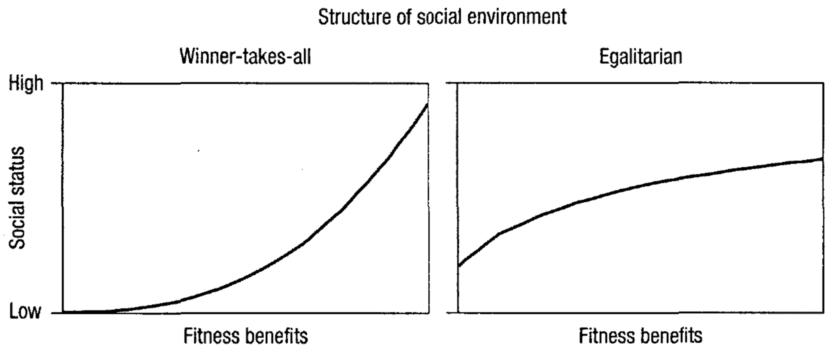

Figure 16.4
Relations between evolutionary fitness and status within a peer group. In hierarchical winner-takes-all environments, the typical alpha male will have preferential access to mates and resources. In this context, it may make sense to take large risks to increase one's social status. In a more egalitarian social structure, in contrast, the fitness benefits are more equally distributed and taking large risks to gain social status has little payoff in terms of fitness benefits. (Inspired by Kacelnik & Bateson, 1997.)

distribution of resources (Wolfe, Frank, & Cook, 1996). As a result, there may be a convex relationship between social status (place in hierarchy) and fitness benefits (see figure 16.4). Evolutionary models suggest that there is more risk-seeking behavior in environments with convex fitness curves than in those with concave fitness curves (Kacelnik & Bateson, 1997). Thus, in a developmental period in which the peer social network and the establishment of one's social status is of paramount importance, the network's structure itself may promote risk-taking behavior (van den Bos, Crone, Meuwese, & Güroğlu, 2018).

16.5 *Sturm und Drang*

A time-honored view of adolescence is that it is a period of pathological—but, thankfully, transient—trials and tribulations (*Sturm und Drang*) on the way to adulthood (Hall, 1904). It seems that raging hormones (Buchanan, Eccles, & Becker, 1992) or unfinished brains (Bell & McBride, 2010) are throwing a wrench in the works. From this perspective, adolescence is a nuisance for adolescents and everybody around them—but fortunately they grow out of it. An ecological perspective, as outlined here, offers a different view, emphasizing the key developmental tasks that adolescents face and arguing that typical adolescent behaviors may have an adaptive core. In addition, it adds nuance to classic models of development focusing on growth or improvement. These models implicitly assume that the function of development is to reach the adult phenotype; accordingly, they conceive of cognitive functions as a series of intermediate stages on the way to completion. The ecological approach—while acknowledging developmental growth and decline in cognition—instead emphasizes the need to understand the structure of the environment and the mind–environment interaction. Most investigations of adolescent behavior are implemented in the laboratory, often using experimental stimuli that do not accurately reflect the key structural elements of the adolescent world; these artificial settings do not offer the insight necessary for deciphering the logic of adolescents' observable behavior.

By drawing on research on decisions from experience (see chapter 7), we have illustrated how insights can be gained by designing experimental microworlds that are better proxies for the decisions adolescents face. In addition, we have identified avenues for exploring the perceived structure of uncertainty in the adolescent environment. In our view, what is required next are ecological analyses of the social and nonsocial environments that adolescents seek out and experience. Understanding the payoff structures, affordances, and constraints of these environments will give a more nuanced perspective than the pathological, or simple cognitive growth, views. Ultimately, an ecological view also promises to inform interventions to prevent the most negative consequences of adolescent behaviors. For instance, it may help us understand why the introduction of skate parks may have a positive influence on youth development, even though the skating scene itself is often (wrongly) associated with deviant behavior. Adolescents become adults by interacting with the environment; relatives, teachers, and society cannot lock teenagers in their rooms and wait until they emerge as well-behaved adults. Parents who often feel that their budding adult landed from another planet may find some comfort in taking an ecological view, which suggests that the adolescent world is indeed different in some ways, and it is impossible to fully understand adolescent behavior without understanding these worlds as well. Remembering that in some places, more than 99.9% of adolescents survive this turbulent period (Willoughby et al., 2014) might make it easier for parents, guardians, and mentors to keep a cool head. In the meantime, more research into Planet Adolescence is needed to eventually help teenagers navigate their world even better.